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The Effect of Automobile Head-Up Displays on Driver Attention

by

Becky L. Hooey

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "The Effect of Automobile Head-Up Displays on Attention" submitted by Becky L. Hooey in partial fulfillment of the requirements for the degree of Master of Science.

Supervisor, Dr. D. W. Kline, Psychology

Dr. J. K. Caird, Psychology

Dr. R. E. Dewar, Psychology

Dr. R. Wardell, Environmental Design

Sept 13 1995
Date

Abstract

Automobile head-up displays (HUDs) were developed to allow drivers to view vehicle status information without taking their eyes off the road. Research (Armour, 1984; Kiefer, 1990) suggested that presenting information in a HUD may minimize the visual scan time associated with head-down displays (HDDs). However, the extent to which HUDs increase problems of divided attention, attention switching and attentional capture is unclear and was examined in the present research. A driving simulation task was used that required participants to perform a compensatory tracking task while completing visual search tasks or verbal-memory tasks presented in a HUD or HDD. Driving (tracking) performance, braking response time to events on the roadway, and latency for display tasks were measured. Attentional capture was examined by presenting the visual search and verbal-memory tasks in a HUD that participants were instructed to ignore. Results indicated that, compared to HDDs, HUDs were associated with better critical event detection and display task latency. However, there was evidence that HUDs may overload the attentional capacity of the driver adversely affecting driving performance. No evidence was found to indicate that attentional capture was increased by HUDs. Theoretical and design issues associated with automobile HUDs are discussed.

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Table of Contents

List of Tables

List of Figures

List of Figures (Continued)

List of Appendices

Introduction

The primary objective of the present study was to examine the possible attentional problems associated with automobile head-up displays (HUD), and to determine the extent that they pose safety hazards to road users. Secondarily, this study attempted to determine the nature and complexity of information that can safely be presented in the HUD without posing safety concerns for road-users.

A HUD is a virtual image in which symbology is displayed so that it appears to be located at some distance beyond the cockpit, cab, or workstation (Weintraub and Ensing, 1992, p. 1). HUDs were developed in the 1940s to enable fighter pilots to read critical display information without looking away from the outside environment. Aircraft HUDs provide pilots with information about the location of their aircraft with respect to the environment through which they are flying. This is necessary for pilots to properly guide their aircraft because the flying environment does not always provide pilots with reliable visual navigation information. Automotive HUDs typically do not provide information about driver location with respect to the road because the driving environment is often sufficient. Thus, HUDs have been used most commonly to provide secondary status information that is not readily available in the environment, such as the speedometer and directional signal lights. As a result, most of the automobile HUD research has focused on the speedometer image.

Critical warning information, such as collision avoidance systems which warn drivers of impending collision, may also be presented in an automobile head-up display. It is also anticipated that environmental information, such as vision enhancement systems (VES), may be presented via a HUD. The intent of a VES is to provide information about the environment that is otherwise unavailable to the driver, such as in heavy fog or snow conditions. Very little research has explored the various types and complexity of information that can safely and effectively be presented in an automobile HUD. The present study examines automobile HUDs which present secondary status information as these are most prominent in current automobile HUDs. Recently, HUDs have been integrated into commercial automobiles. However, little research has considered the differences between aviation and automobile HUD applications. Also, the fit between HUD technology and driver's attentional capabilities has not been adequately addressed in the literature.

Human factors evaluations of this relatively new technology are needed to ensure that HUDs do not exceed the visual and attentional capabilities of the driver. Recent evidence has suggested that HUDs may facilitate the process of switching attention (Sojourner and Antin, 1990), thus increasing the likelihood of responding to important events on the roadway, and minimizing visual scan time required to retrieve information from the display (Kiefer, 1991; Armour, 1984). However, HUDs may also be disadvantageous because they overload drivers with information thereby exceeding their attentional capacity. Also, HUDs may draw attention toward the display and away from the external environment (Fischer, Haines, and Price, 1980; Wickens, Martin-Emerson, and Larish, 1993; Long and Wickens, 1994) .

The objective of this research is to explore the nature and complexity of information that can safely be displayed in an automobile HUD to maximize the benefits (improved critical event detection and reduced visual scan time) while minimizing potential costs (attentional overload, and attentional capture). The visual parameters that constrain the design of HUD applications will be discussed, followed by the attentional issues associated with visual scanning, selective attention, divided attention, and attentional capture. HUD research from aviation and driving domains is integrated throughout the review.

HUD Visual Parameters

HUD Legibility

Weintraub and Ensing (1992) and Harrison (1994) provide comprehensive reviews of the research aimed at optimizing the legibility of HUDs. The visual parameters, as displayed in Table 1, have been principally based on aircraft HUDs. To date, minimal research has extended these criteria to the driving domain where task information may be less critical and the visual capacities of the operator much more variable.

HUD Location

One important unresolved issue associated with HUDs is the optimal placement of information with respect to the drivers' normal line of sight. Weintraub and Ensing (1992) and Harrison (1994) provide comprehensive reviews of the literature. A series of performance-based studies (Sakata, Okabayashi, Fukano, Hirose, and Ozono, 1988; Okabayashi, Sakata, Furukawa, and Hatada, 1989; Okabayashi, Sakata, Furukawa, and Hatada, 1990) have utilized a dual task method to determine the ideal HUD location. In these studies, participants performed an environment monitoring task and a HUD task simultaneously. To simulate environment monitoring, participants were asked to determine the orientation of Lazy E acuity targets (i.e. capital E's at 4 different orientations) when presented at various distances in front of the participant. The HUD task, which required participants to report a two digit number, was placed at various locations from 0 to 20 degrees below the normal line of sight, and from 0 to 11 degrees to the right of the normal line of sight. It was found that both environment and HUD monitoring was facilitated when the HUD was closest

Table 1.

HUD Legibility Parameters.

Legibility Parameter	Recommended Values
Luminance-Contrast Ratio	Minimum 1.15 : 1 Preferred: 1.5:1
Display Resolution	Minimum 16 lines/symbol height Preferred 20 lines/symbol height
Symbol Height	Alphanumerics: 28 minutes or arc Non-Alphanumerics: 34 minutes or arc
Symbol Width	75 % of character height
Stroke Width	Stroke width to height ratio: 1:5 to 1:8 Minimum: 3 minutes
Character Spacing	50% of character height for grouped letters 100% of character height between words
Character Font	Preferred: Lincoln/Mitre Acceptable: Leroy
Colour	Monochromatic; green

Note: Adapted from Weintraub and Ensing, 1992.

to the normal line of sight. This conclusion must be interpreted with caution because the environment monitoring task (identifying Snellen figures) was highly artificial. That is, an identification task is very different than a constant flow-field produced by driving (Schiff and Arnone, 1995).

Ward, Parkes, and Crone (1994) examined the issue of display location relative to driving background scenes of varying complexities. Participants were required to maintain lane position of a simulated vehicle while responding to two HUD tasks. The HUD contained a two-digit number, analogous to a speedometer, in the lower left quadrant. Participants monitored the digital number and responded via a button on the steering wheel when deviations exceeded a specified magnitude, which varied among participants. A Landolt C acuity target was presented intermittently in one of the other three quadrants and participants were required to press a foot pedal when the C was of a specified orientation. Two HUD positions were tested: 1) centered on the normal line of sight; or 2) three degrees below the line of sight. The authors concluded that while the HUD centered on the normal line of sight increased HUD task response times, the lower display reduced the problem of decreased conspicuity of symbols displayed against complex backgrounds. Further, it was suggested that HUDs placed directly at the normal line of sight may introduce conflict between superimposed images and driving scene backgrounds. The authors conclude that further research is required, utilizing backgrounds and HUD tasks more relevant to driving, before an ideal HUD location can be determined.

HUD Projection Distance

Minimal research has addressed the issue of the ideal distance at which the HUD image should be projected in front of the driver. In aviation and driving, the operator must continuously change their visual accommodation between the outside environment, and the instrument panel. The time required to change visual accommodation (i.e., for the ciliary muscle to adjust the shape of the lens to bring the image into focus on the retina) constrains the acquisition of information. Aircraft HUDs were collimated at optical infinity to reduce the need for pilots to move their gaze from the blank visual field to the instrument panel. However, there is some doubt regarding the validity of this assumption because many observers in such cue-impoverished conditions naturally shift to an accommodative resting state nearer than optical infinity (see Roscoe 1984, 1985, 1987a, 1987b).

Automobile drivers are required to change their focus from the external environment to the instrument panel located 50 to 70 cm away. Presenting an automobile HUD at optical infinity would encourage drivers to focus closer to their driving focus point. However, there is some concern (e.g. Roscoe, 1987) that is may create conditions of 'positive misaccommodation'. This causes the whole visual scene to shrink in apparent size, and as a result distant objects seem smaller and thus farther away than they really are. This would be problematic in a dynamic driving environment where accurate speed and distance estimates are vital. The issue of misaccommodation, however, is contentious.

Little research has examined the ideal projection distance that will maximize performance for drivers of all ages. Inzuka, Osumi, and Shinkai (1991) considered the older adults' reduced ability to visually accommodate from near to far and vice versa. They tested young and older adults' ability to monitor a HUD speedometer in a simulated driving task. They found that older participants' performance was facilitated as the HUD image moved from 1 to 2.5 m away from their eyes, but there was no significant improvement once the HUD was moved past 2.5 m. Thus, the authors recommended that HUDs be projected 2.5 m away from the driver's eyes. Kato, Ito, Shima, Imaizumi, and Shibata (1992) replicated the previous study and found that HUD images projected farther than 2.0 m no longer improved performance for older drivers. Thus, it is generally agreed that projecting the HUD image between 2 and 2.5 m away from the driver's eyes will optimize performance for drivers of all ages. Further research is required to determine whether these projection distances are also appropriate for various road types (straight or curved), driving environments (urban, rural, or highway), and visibility conditions (rain, night, fog, etc.).

Head-Up Display Issues

Beyond the parameters of basic visual functioning that constrain the design of HUDs, a number of perceptual and attentional issues have emerged that require systematic consideration. These include visual scaning, divided attention, selective attention, and attentional capture.

Visual Scanning

HUDs have been cited as advantageous because the greater spatial contiguity of the display and the external environment may reduce the time required to retrieve information from the display. The accumulated evidence suggests that HUDs reduce or eliminate the need to move the direction of gaze, thus, making the process of gathering information from the instrument panel faster (Armour, 1984; Kiefer, 1991). According to Wickens (1992), visual scanning is necessary to attend to two spatially separate visual sources of information, a process necessitating saccadic eye movements which constrain performance. For example, a 5 degree saccade requires approximately 200 ms to initiate, lasts about 30 ms, and requires another 2 ms for each additional one degree increase in saccade magnitude (Card, Moran, and Newell, 1986). A HUD located 4 degrees below the horizontal line of sight would require approximately 22 ms less visual scan time than a HDD, typically located 15 degrees below horizontal. Although, faster uptake of display information will allow drivers to return their eyes to the road faster, the practical significance of saving 22 ms in the driving environment would amount to 0.6 m if required to stop at 100 kph. If a large number of visual scans are required to extract information from a complex display, the "HUD advantage", however, would be more substantial.

A common finding is that it takes less time to read a HUD display. In the driving domain, Armour (1984) was one of the first to compare speedometer reading times for both analog and digital speedometers located either head-up or head-down. HUDs had an advantage over HDDs of about 100 ms. Despite evidence to the contrary, Kiefer, (1991) suggested that HUD users may not show a net benefit from reduced visual scan times because drivers make more frequent glances to the HUD than the HDD. Kiefer compared speed control and visual sampling behaviour with HUD and HDD digital speedometers in a real driving environment. Results confirmed that visual search time in a speedometer reading task can be speeded by 100 to 150 ms when using a HUD. However, using eye movement trackers, he also found that drivers made more frequent glances toward the HUD than the HDD, but the duration of each HUD fixation was shorter. Overall, approximately equal amounts of time were spent viewing the HUD and HDD, despite marked differences in viewing patterns. Kiefer suggested that people have quicker access to speedometer information displayed in a HUD, but that they don't actually spend more time monitoring the forward roadway because the HUD causes them to monitor their speed more frequently. Thus, the cost of the sum of glances to a HUD appeared to negate their scan advantage. However, Kiefer's results also suggest that a novelty effect was operating. His participants glanced at the speedometer 6.6 times per minute during the first of four sessions and 3.9 times per minute during the last of the four sessions. Exposure to a HUD naturally draws attention to it. With time, and depending on the salience of the display information, glance frequency would be expected to decline. Visual sampling of the HUD approached comparable levels of the HDD as a function of experience. Visual sampling patterns as a function of HUD use need to be examined further, over longer habituation periods, and across a variety of tasks that vary display salience.

It is clear that HUDs produce faster display reading times by reducing the time required to move the eyes toward the display. Many early studies confounded visual accommodation and visual scan time by using a HUD projected at some distance in front of the driver, and a HDD presented at a typical distance of 50 to 70 cm. The present study seeks to determine if a HUD advantage exists solely due to visual scan time by projecting the HUD and HDD at the same distance.

Divided Attention

The visual scanning research suggests that drivers switch attention from one source to another in a serial fashion. This logic suggests that if the driver's eyes are on the display, they must not be monitoring the road. However, it is clear that even under routine, low-traffic conditions, the driver can attend to several tasks at once. Usually drivers can do this quite effectively because many of the tasks become so highly automated with experience that under normal conditions, the demands of dividing attention are generally within the limits of the driver's attentional capacity. However, as driving demands increase, (e.g., high density traffic, intersections, poor weather, unfamiliar environments), the demands on divided attention may exceed the driver's capabilities, in which case processing of one or more information sources may be slowed.

It is commonly believed that because HUDs allow drivers to keep their eyes on the roadway, drivers can simultaneously attend to the task of driving and the information presented in the HUD. This allows for parallel processing, or simultaneous processing of the two domains. In driving, Kaptein (1994) found beneficial effects of an analog speedometer presented in a HUD as compared to the same speedometer presented heads-down. In a driving simulator, Kaptein's participants drove along a curved road while keeping their driving speed as close as possible to a specified target speed. To artificially increase workload, sidewinds and adverse winds were varied. Kaptein found that HUD drivers performed better on the lane keeping task and speed maintenance tasks than the HDD drivers. This result was attributed to the HUD allowing simultaneous processing of the lane maintenance task and the speed maintenance task. This is one of the only studies to measure performance on a lane maintenance task, however participants' ability to monitor the roadway for critical events was not examined. This limitation was addressed in the present study by adding a critical event detection task to the lane maintenance and display tasks.

Although HUDs may facilitate parallel processing, they do not guarantee that it will occur (Wickens, 1992). Results from Neisser and Becklen's (1975) study suggests that drivers' visual attention limitations may actually hinder the simultaneous processing of HUD information and environmental information. Their participants viewed two superimposed video screens on which two activities were shown. One scene depicted two people playing the "hand game" while the second scene depicted three men passing a basketball. Participants were required to follow the activity in one screen and ignore the other. They could do this so effectively that odd events in the unattended episode were rarely noticed, and participants reported that it was difficult to monitor both episodes at once, despite the fact that they shared the same location in space. Neisser and Becklen suggested that this may have occurred because perception is organized so that a particular structured flow of information can be followed and the unrelated one cannot (p. 493). Thus, the extent that parallel processing may allow drivers to simultaneously maintain their lane position while obtaining information from the HUD is unknown.

Selective Attention

Driving requires continuously sampling multiple sources of information, such as the roadway, pedestrians, vehicles, signs, and the instrument panel for information. There are two aspects of selective attention: 1) attention switching, or efficiently switching attention from one source to another, that is, to events that are critical for the safe operation of the vehicle (e.g., see Gibson and Crooks, 1938), and 2) attention allocation, or focusing attention on the relevant source of information.

Attention Switching. The first element of selective attention, the ability to switch attention between information sources, may be the most critical (Parasuraman and Nestor, 1991). Several studies (e.g., Avolio, Kroeck, and Panek, 1985; Kahneman, Ben-Ishai, and Lotan, 1973; McKenna, Duncan, and Brown, 1986) have reported moderate correlations (.3 to .5) relating errors on an auditory selective attention, or dichotic listening task, to vehicle accident rate. Kahneman, Ben-Ishai, and Lotan (1973) suggested that the inability to switch attention is a significant contributor to driving accidents. Also, Lim and Dewar

(1988) found that performance on a dichotic listening task was strongly correlated with accident rate in city bus drivers.

Kahneman, Ben-Ishai, and Lotan (1973) first suggested that the ability to reorient attention to a new source from a prior state of attention is more difficult than the initial adoption of a focused-attention state. Posner, Walker, Friedrich, and Rafal (1984) have referred to this as the ability to disengage and engage attention, a capacity that may allow for a fast response to unexpected events on the roadway. Recently, Duncan, Ward, and Shapiro (1994) examined how long an object which must be identified continues to occupy attention. Participants' attention was engaged on one object, which they were asked to identify. At various intervals afterwards, a second object was presented and interference of the first object on the second was measured. The authors reported that responses to the second object, if presented between 0 and 500 ms after the first object, were slowed because attention dwelled on the first object. This evidence suggests that once attention is engaged on one object, attention may remain there for several hundred milliseconds before attention can be switched to a new information source.

A critical issues that must be addressed is whether attention remains fixed on the HUD, thus slowing the switch of attention back to the roadway. Weintraub and Ensing (1992) suggested that delays in attention switching may occur because of the absence of cues that normally indicate that a switch from the HDD to the environment is in progress. These cues include the physical process of looking up, changing optical focus and changing eye convergence. Not only do Weintraub and Ensing (1992) provide little evidence to support this statement, there is a substantial amount of evidence in the cognitive literature to suggest that the eye movements are not necessarily associated with attention switching.

The relative independence between eye movements and attention movements was discussed by Klein (1979) who stated that the readiness to move one's eyes does not induce an attentional shift and attentional shifts do not necessarily result in oculomotor readiness. The literature has long noted that an observer may shift attention from one location to another without moving the eyes (Posner, 1980; Eriksen and Hoffman, 1972). Posner (1980, p. 5) called this 'covert orienting of attention'. Evidence in support of covert attention comes from the finding (e.g. see Eriksen and Hoffman, 1974; Posner, Nissen, and Ogden, 1978; Posner, Snyder, and Davidson, 1980) that prior knowledge of target location (cueing) facilitated performance for a briefly-presented target, and incorrect cueing slows performance. Thus, despite eyes remaining focused on a central fixation point, response times were faster to respond to the presence of a target because attention was shifted to the cued area. This suggests that attention can be oriented to a designated peripheral location independently of eye fixation, and improve the processing of a stimulus occupying that location (Posner, 1980). Furthermore, Remington (1980) showed that, although eye movements and shifts of attention are elicited by the occurrence of a peripheral stimulus, the movement of attention precedes the movement of eyes. It was estimated that a move of attention requires as little as 50 ms, whereas a visual saccade required to foveate an object, requires at least 230 ms. This suggests that covert switches of attention, which are possible with HUDs because eye movements are not necessary, may be faster than the overt switch of attention dictated by the HDD. However, extensions of these experimental findings to automobile HUDs remains unexamined.

Aviation studies have examined the ability of pilots to switch attention from the HUD to the far domain, and the far domain to the HUD (Wickens, Martin-Emerson, and Larish, 1993). Both studies used a similar methodology that examined the detection of critical events in a simulated flight environment. Twenty instrument-rated students flew a series of landing approaches using either a HUD or a display presented 8.5 degrees head down. A participant's ability to switch attention from the display to the outside environment was measured from the time they broke through the clouds to when they verbally said the colour of a runway light. Results showed that the runway signal was not detected significantly faster using the HUD (mean detection time was 1.1 seconds) than the HDD (mean detection time was 1.28 ms). Thus, attention switching from the display to the environment was not affected by display location. The time required to shift attention from the environment to the display was measured by the time required to respond to discrete events in an instrument panel. Results indicated that the response times for the HUD condition (1.3 seconds) were significantly faster than with the HDD (1.5 seconds). However, the authors noted that they were unable to determine where the pilot was attending prior to the onset of the instrument task event. As a result, it is not clear whether attention was shifted from the environment or elsewhere on the instrument panel. In conclusion, the study revealed that HUDs may have facilitated attention switching from the environment to the display, but there was no evidence that switching from the display to the environment was facilitated.

In the driving domain, the ability to switch attention from the display to the roadway is critical to detecting and responding to changes in the traffic environment; the ability to switch from the environment to the display is often less critical. Sojourner and Antin (1990) examined the former by comparing the effects of a HUD and HDD speedometer on perceptual driving tasks in a simulated environment. Their participants viewed a video tape of a car traveling along a route recorded from a driver's viewing perspective. While viewing, participants performed tasks related to navigation and speed monitoring presented in either the HUD or the HDD. Also, participants were required to press a mouse button in response to the onset of a discrete cue (a green ball) that appeared on the left, right, or center of the roadway. Speed monitoring performance was superior for drivers in the HUD condition than the HDD condition. However, no differences were found between HUD and HDD use in the navigation task. Nearly flawless performance in both conditions indicated a ceiling effect for the tasks and precluded differentiating between the two displays. In the HUD condition, 3 of 90 cues presented were missed, whereas the HDD group missed 9 of 90. HUD users had significantly faster reaction times (570 ms) to cue onset than did the HDD users (1010 ms). Thus, the HUD improved performance on the display task by approximately 440 ms, enabling participants to respond more quickly to obstacles on the roadway. They attributed this reaction time advantage to the reduction in time needed to shift their attention, provided by the HUD. They also noted that the time saving of 440 ms was of practical significance, because it translates into a distance of 12.2 meters at 100 kph. They concluded that with the HUD, drivers could efficiently switch attention from the HUD to the road. However, because participants did not perform a driving or tracking task, participants had more attentional resources to direct to the critical event detection task than might normally be available while driving. Because this is the only study in the driving domain that has attempted to address attentional switching and the attentional demands placed on participants were unlike those found in driving, the present study sought to correct these limitations. It will examine the ability of drivers to shift their attention from the display to the road; using the appearance of a pedestrian in the roadway to cue the attentional shift.

Attention Allocation. The second element of selective attention refers how vehicle operators allocate their attention. One explanation of attention allocation comes from the supervisory/control literature (e.g., Senders, 1964). This literature suggests that operators scan the environment and allocate attention through visual fixations to various information sources. Optimal sampling has been examined in laboratory studies (e.g., Moray 1981, 1986) in which the participants are presented with two or more information sources which provide information at semi-predictable rates. Moray found that people develop a mental model of the statistical properties of events in the environment and they use the model to guide their visual sampling. The mental model is a set of expectancies about how frequently and when important events will occur in each information source. Further, people learn to sample information sources with higher event rates more frequently and those with lower rates less frequently. Therefore, if the operator receives more information from the display than the environment, he/she will sample the display more frequently.

If the supervisory/control model is extended to HUD use, operators would probabalistically allocate their attention by determining what information source, the instrument panel or environment, is most likely to provide the information needed. Therefore it is likely that pilots would sample the HUD frequently as it typically provides critical information (i.e. air speed) not provided in the environment. Automobile HUDs, which generally do not provide critical information, would likely be sampled less frequently.

The supervisory/control literature also suggests that the time between sampling is determined by the trade-off of two factors: the growth of uncertainty of the state of the unsampled source, and the cost of taking a sample (Carbonnell, Ward and Senders, 1968; Sheridan, 1972). Wierwille (1993), provided a description of how drivers sample their environment and traditional instrument panels. When driving, the forward scene is the primary information source. The driver may occasionally look elsewhere but must still pay close attention to the forward scene because it provides a great deal of important information regarding vehicle control and hazard detection. Under high load conditions, such as heavy traffic, or a curving road, it becomes more hazardous to look away from the forward roadway. However, under light load conditions, such as little traffic, and straight roads, the driver can look away for longer periods of time. Drivers, therefore, treat driving as the primary information source, and the instrument panel or other information display as secondary.

Wierwille developed a model to explain how most drivers time share the tasks of obtaining information from displays within the vehicle and driving. First, the driver samples the display and returns to the forward view, samples the task, returns to the forward view, etc., until the information is gathered from the display. In some cases, a single sample of the in-vehicle display is required; for more complex displays, several samples may be required. Wierwille (1993) estimated that 1.6 seconds is the maximum time that a driver can look away from the forward view without feeling uncomfortable about the uncertainty of the forward scene. The visual sampling patterns that pilots and drivers use with a HUD have not been well documented. It is unclear whether the attention allocation model, developed by Wierwille to examine traditional instrument panels, would be the same when driving with a HUD.

Attentional Capture

Attentional capture, often termed "cognitive capture" in the HUD literature, occurs when a stimulus draws a person's attention to it to the exclusion of other stimuli (Weintraub, 1987). A driver's gaze could be drawn to the HUD during onset, or stimulus change, or due to normal visual sampling. Efficient and safe driving depends on the selection and subsequent processing of the relevant information, either the roadway or visual display. HUDs may be problematic if they capture the attention at the expense of attending to the external scene. Empirical and anecdotal support for attentional capture has been reported in both flight (Fischer, Haines, and Price, 1980; Roscoe, 1991) and driving (Okabayashi, Sakata, Fukano, Daidoji, Hasimoto, and Ishikawa, 1989). Specifically, vehicle operators failed to notice information in the outside world while monitoring information displayed in the HUD. The degree that attentional capture may contribute to accidents has been vigorously debated (see Roscoe, 1991).

Attentional capture has been examined in aviation-simulation studies (Fischer, Haines, and Price, 1980; Long and Wickens, 1994; Wickens, Martin-Emerson, and Larish, 1993) by surprising pilots with an unexpected airplane blocking the runway and observing the pilots' response. In these studies, it was expected that a pilot monitoring the outside world would detect and respond to the runway obstruction quickly, whereas a pilot that is drawn to the display, would be slower to respond to the runway obstruction. Fischer, Haines and Price (1980) found that the time required to detect and respond to the unexpected airplane was longer when flying with a HUD than with the HDD, and some participants failed to notice the airplane at all when using the HUD. Long and Wickens (1994) also utilized this methodology and found that the HUD produced slower responses to the unexpected event. Wickens, Martin-Emerson, and Larish (1993) failed to find a HUD cost for detection of the unexpected incursion, however, they did find a non-significant trend in this direction. Long and Wickens (1994) suggested that given the low power dictated by collecting only one data point per participant which is necessary for the obstacle to be unexpected, the trend was still of practical importance. It is still unclear, however, why the pilots failed to notice the airplane on the runway. Two theoretical constructs, stimulus-driven and goal-driven allocation of attention, provide some insight into the issue of attentional capture.

Stimulus-Driven Selection. The stimulus-driven or bottom-up selection theory suggests that attention is captured by salient properties of the stimulus even if they are irrelevant to the task (Yantis and Jonides, 1984). For example, human operators are drawn to objects in the visual field that are large, bright, colorful, or moving (Wickens, 1992). It is reasonable to assume that a flashing red warning light in the HUD would draw the drivers attention toward it. Unlike HUDs, HDDs are not in the field of view while driving, and thus, are not likely to be subject to attentional capture.

Other research supports the possibility that attention would be drawn to the HUD based on its visual salience. For example, in 1959, Moray found that participants listening to one of two voices in a dichotic listening task, often reported hearing highly familiar words such as their own names spoken by the ignored voice. It was as if the processing of highly familiar and normally relevant words was so automatic that they were processed involuntarily without attention. Evidence in the visual domain is provided from Eriksen and Eriksen (1974) who measured participants' ability to detect the presence of a letter among two adjacent irrelevant letters that were to be ignored. Results showed that the irrelevant letters slowed response times to the target letter relative to the control condition. Thus, it was concluded that if two perceptual sources are close together, they will both be processed, even if only one is desired. Such processing would inevitably lead to some competition (intrusion or distraction) at a perceptual level. These studies characterize stimulus driven allocation of attention in both the visual and auditory domains.

Goal-Driven Selection. Goal-driven or top-down selection dictates that knowledge or expectancies about a task determines what is selected for the allocation of attentional resources (Hillstrom and Yantis, 1994). This position is compatible at a discrete level with the supervisory/control context of visual sampling discussed previously. For example, when presented with both the external environment and the HUD, an operator can direct attention to either information source, depending on the importance of the information that they provide. A pilot may choose to attend to the HUD, as it provides more information than the blank visual field of the external environment. On the other hand, an automobile driver may choose to attend to the roadway, as the HUD only provides peripheral information which is often not sufficient for safe operation of the vehicle. Furthermore, Bacon and Egeth (1994) suggest that when the two approaches, stimulus-driven and goal-driven, are pit against each other, such that a visually salient stimulus occurs in addition to goal-directed instructions, the goal-directed allocation of spatial attention overrides the stimulus-driven attentional capture. Although, not tested in a driving environment, Bacon and Egeth's results suggest that automobile drivers may not be distracted by an abrupt onset of the HUD when they are in an attentional state focused on the roadway. The issue of whether attentional capture occurs with automobile HUDs has yet to be addressed. The present study will do so by making the HUD transiently relevant, and determining if driving and critical event detection performance deteriorate due to the presence of the irrelevant HUD.

Present Study

Research suggests that information displayed in a HUD may effectively minimize the longer visual scan times typically associated with traditional HDDs. However, the effects on divided attention, attention switching and attentional capture, at this time, are unclear. The present research examined these issues to determine whether the visual scan advantage achieved by HUDs is greater than the potential attentional costs associated with their use. To achieve these manipulations, a driving simulation, dual task paradigm, was utilized. This required participants to perform a compensatory tracking task while completing either visual search tasks or verbal-memory tasks in a HUD or HDD. Driving performance was operationalized by lane position deviations. Participants' braking response time (BRT) to critical events, the appearance of a pedestrian, in the roadway was also recorded.

The fundamental difference between the aviation and driving domains is that HUD information in aviation is critical to the safe operation of the aircraft, whereas in automobiles it is almost always secondary to the task of driving (except possibly for vision enhancement systems), and is not essential for control of the vehicle. The present study examined if drivers can use a goal-driven approach to allocate their attention to the roadway, instead of being drawn to the display as predicted by the stimulus-driven approach. An instructional set was used to vary the relevance of HUD-presented information, by instructing participants, on certain trials, to ignore the display. Tracking performance and critical event braking times on the display-irrelevant trials were compared to baseline performances to determine whether performance suffers as a result of the irrelevant HUD information.

Hypotheses

1. Because the HUD allows the participants to keep their eyes on the driving task, it was expected that overall tracking performance, while attending to the display, would be superior in the HUD condition than the HDD condition. The HDD, which requires participants to move their eyes and attention, from the tracking task, ensures that divided attention cannot occur, thus performance was expected to suffer. Furthermore, a display location by task difficulty interaction was expected. Tracking performance in the high-task load condition, that is difficult display task and difficult tracking, was expected to deteriorate because the tasks (visual search and verbal-memory) would overload the participants' attentional capacities.

2. Based on the findings of Kiefer (1991) and Armour (1984), it was expected that response latency for both the visual search task and the verbal-memory tasks would be faster when presented in the HUD than the HDD. It was expected that the visual scan time needed to move the eyes from the road to the HUD will be shorter than the time needed to move the eyes to the HDD because the distance is shorter.

3. Critical event detection, or the ability to disengage attention from the display and engage attention to the traffic environment, was expected to be slower with the HDD than with the HUD. It is unclear from past HUD research if

display location affects attention switching, however, the cognitive psychology literature suggests that covert shifts of attention, shifts that do not require eye movements, require less time than overt shifts of attention. Thus, to the extent that HUDs allow covert shifts of attention, critical event detection should be faster. Further, the distance from the HDD to the road necessitates overt eye movements, and thus overt attention switching.

4. Attentional capture, being drawn to the HUD when it is not relevant, was tested by instructing the participants that the HUD/HDD was no longer relevant and that they should ignore it, but continue with tracking and critical event detection tasks. The stimulus-driven approach of attention allocation suggests that driving performance and obstacle braking reaction times would be worse in the HUD-irrelevant trials because participants would be drawn to the visually salient HUD. This same effect would not be expected in the HDD condition because the display is out of the field of view while driving. The goal-directed approach of attention allocation and the supervisory/control visual sampling theory, suggested that drivers would be able to effectively ignore the display because the information provided in the simulated roadway (i.e., the lane) was more relevant than the display.

Attention paid to the HUD when it is not relevant, operationalized by poorer tracking performance or delayed critical event detection, will provide support for a stimulus-driven allocation of attention. Alternatively, the ability to ignore the display, despite abrupt visual onsets and offsets, as determined by tracking performance and critical event response times that are equivalent to baseline measures, will provide evidence for a goal-driven process.

Method

Participants

Sixteen participants, eight male and eight female, from 20 to 37 years of age, volunteered for the study. Table 2 presents the demographic characteristics of the sample. All but two participants had near acuity of 20/20 vision; the near acuity of the two remaining two participants was 20/30. Participants were permitted to wear their present visual correction (eye glasses or contact lenses) for the experiment. All were licensed drivers, however, two of the participants reported that at the time they did not drive on a regular basis. Of the remaining 14 participants, 79% reported driving in an urban setting 'frequently or very frequently'.

Materials

Visual Testing. Visual acuity was tested at a distance of 70 cm using the A.O. Nearpoint Rotochart. In addition, the Vistech 6500 Portable Contrast Sensitivity test was administered at a distance of 46 cm. Five spatial frequencies (1.5, 3, 6, 12, 18 cycles/degree) were tested.

Questionnaire. A three page questionnaire (Appendix A) was given to participants to ascertain demographic and visual characteristics, as well as driving experience and computer/ video game experience.

Equipment. The tasks were presented on a 21-inch, Nanao high-resolution colour monitor and controlled by a 486-66 Mhz computer. In a setting configured to approximate automobile driving, participants were able to adjust their position and distance from the screen to its most comfortable level. Viewing distances varied from 52 to 75 cm (M = 64 cm) which resulted in a range of angular sizes of the 40 cm wide X 30 cm high screen (30 X 22 degrees to 35 X 26 degrees). Participants manipulated the location of an on-screen icon of

Table 2.

Characteristics of the Sample.

Characteristic		Male	Female	Total
Age (years)	Mean	26	25	26
	Range	20-37	22-29	20 - 37
Acuity* (minarc)	Mean	1.06	1.06	1.06
	Range	1.0 - 1.5	1.0 - 1.5	1.0 - 1.5
Education (years)	Mean	15.5	16.5	16
	Range	12 - 18	16 - 19	12 - 19
Driving Experience (yrs)	Mean	10.13	8.19	9.2
	Range	5-21	4.5-11	5 - 14
Distance / week (km)	Mean	230.63	134.38	182
	Range	50-600	0-350	0 - 600
Hours Driven / week	Mean	7.75	3.81	5.78
	Range	2-14	0-10	0-14
Number of Participants		8	8	16

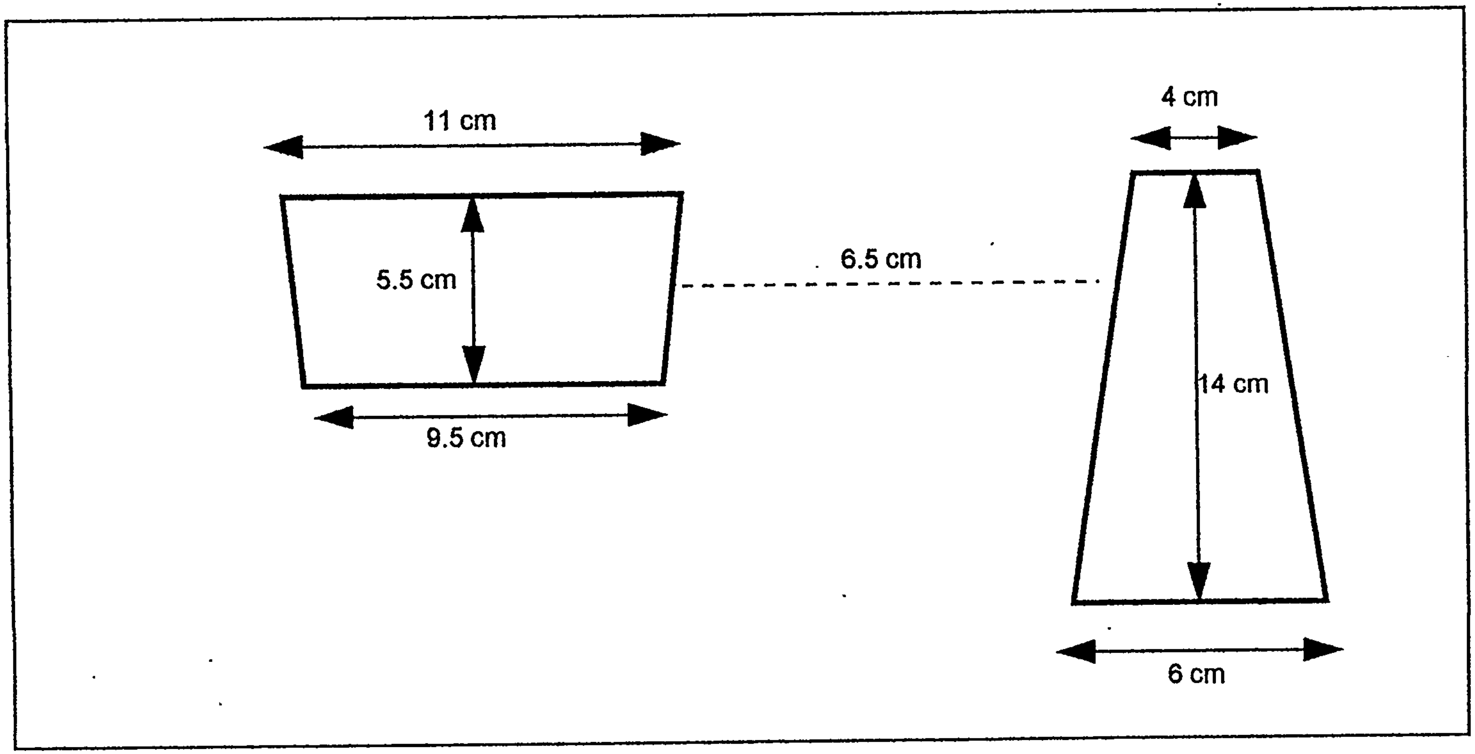
* The ability to resolve details of 1.0 minarc is equivalent to 20/20 vision; where as the ability to resolve details of 1.5 minarc is equivalent to 20/30 vision.

their "car" using a 'Virtual Pilot' flight yoke as a steering wheel. A response button located on each handle of the flight yoke was used to respond to the forced choice display tasks (visual search/verbal-memory) A mock foot-operated brake and accelerator pad (as shown in Figure 1) was configured to record braking reaction time to pedestrians on the roadway. As in an automobile, the brake pedal was 4 cm closer to the participant than was the accelerator pad. The brake pedal was moveable so each participant could adjust the position left and right, and forward and backward.

Software (HUDware). The software (HUDware) controlled the stimulus presentation and data acquisition. It was developed to approximate the task of driving a car by maintaining lane position and avoiding obstacles on the road while responding to information presented in either a HUD or HDD. The software consisted of a scripting utility (user scripts, script compiler, script debugger), event manager, graphical object and animation library, and post-processing utilities.

User scripts were developed to run the experimental trials (see Appendix B for a sample script). Each script contained a configuration section that allowed parameters such as data capture rates, joy stick polling rates, data processing protocols, stimuli durations, and some experimental manipulations (display location, obstacle duration, display task type, and display difficulty) to be set by the experimenter for each block of trials. The body of each script consisted of a series of chronological statements utilized to determine the onset and offset time of each display, and obstacle. Also, scripted in the body were the remaining experimental manipulations such as target state of the display task, obstacle location, and the tracking difficulty level. The scripts were written in ASCII text format and then "debugged" for logical inconsistencies. Extensive pilot testing also verified the logic and format of the scripts. Scripts were

Figure 1.
Brake and Accelerator Configuration



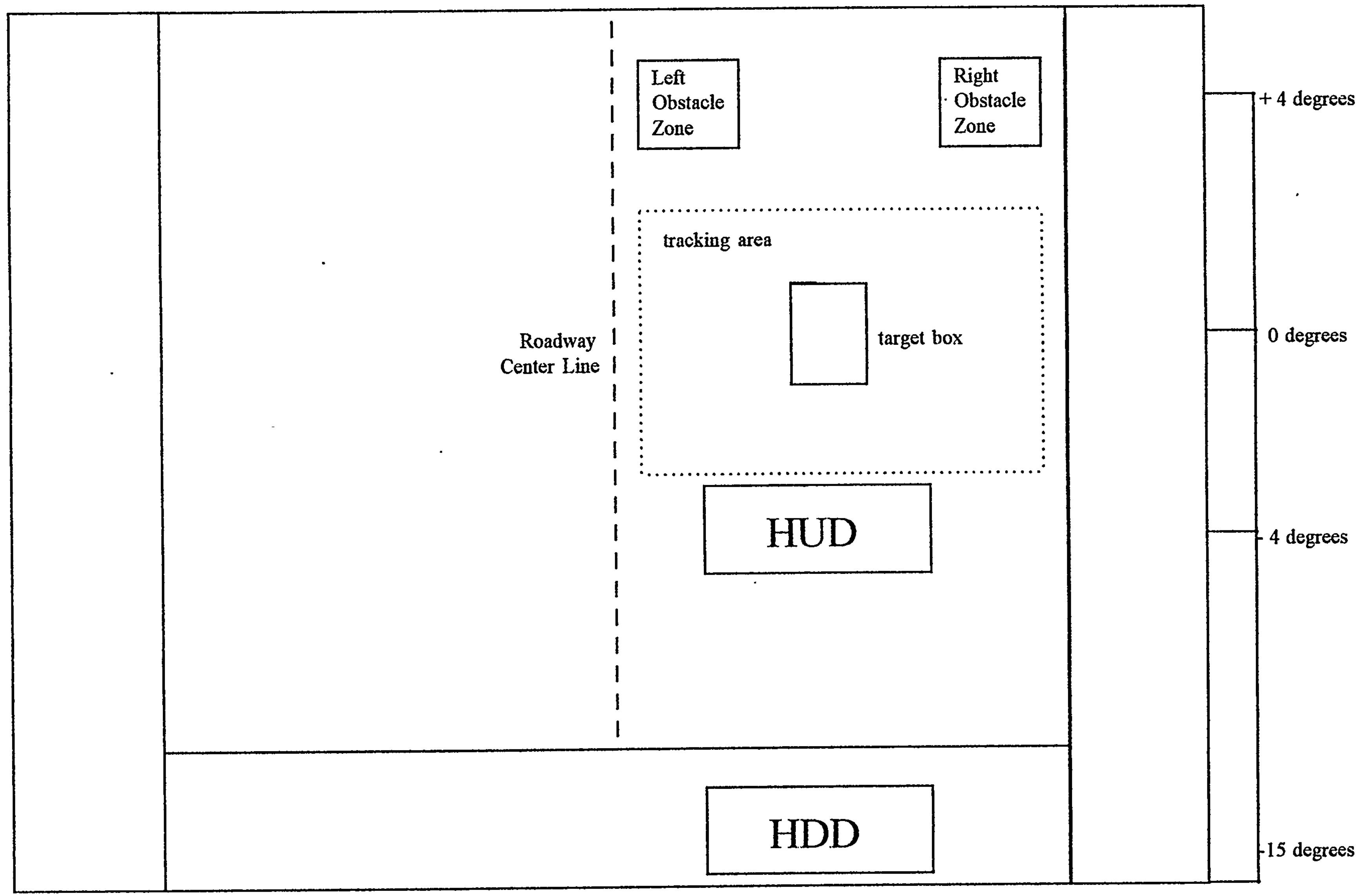
Note: The surface of the brake pedal was 4 cm higher than the surface of the accelerator compiled to provide a binary stream of scripted events, loaded into the event manager module, and finally inserted into an event queue to be processed by the task queue manager at run time.

The event manager can manage up to four serial ports, keyboard input, mouse, and a game port with one or two input devices with an adjustable polling rate based on the 1024 hz real-time clock. The timing resolution of HUDware was 976 microseconds, and lags of no more than 30 ms could be expected. It also provides error reporting, status and debugging mechanisms. The graphical object interface, GROBJ5, utilized a fully object-oriented framework, and operated in a medium-resolution, 640 X 350 16-colour VGA mode. The captured binary output was passed through the post-processor utilities four times to parse the display response (accuracy and RT) data, the critical event detection data, and the tracking performance data, into three separate spreadsheet adaptable files.

Viewing Screens. As shown in Figure 2, the viewing screen was divided into two portions; the external world (simulated roadway) and the instrument panel domain. The plan-view of the roadway consists of a two-lane road, and participants were required to "drive" their car icon (1.79 X 2.69 degrees)[1] in the center of the right hand lane. A target box of the same size was marked in the lane to guide the participants in this task. While driving, a pedestrian icon (.90 X 1.34 degrees), randomly appeared in the driver's lane, forward of the target box. It appeared approximately 4 degrees to the left or right of the center of the lane, and approximately 4.6 degrees above the center of the tracking task. Except for their location, the HUD and HDD were identical and measured 6.37 degrees

[1]Angular dimensions are calculated using the mean distance (64 cm). Appendix C presents the actual dimensions, along with the angular dimensions calculated with the participants' minimum and maximum distances from the screen.

Figure 2.
HUDWare Viewing Screen



wide by 2.69 degrees high. The HUD was superimposed on the roadway, approximately 5.8 degrees below the center of the tracking task. The HDD display was located in the bottom portion of the screen, approximately 16.5 degrees below the center of the tracking task. The vertical separation between the two displays ranged from 9 to 13 degrees dependent on viewer distance.

Experimental Tasks

Tracking Task. Participants maintained a first-order compensatory tracking task as their "car" moved randomly along the 'X' and 'Y' axes. Three levels of tracking difficulty, established by pilot testing, were based on changes in both the velocity and amplitude of the car's movements from the center point of the lane. Participants were required to keep the car centered in the target box marked on the lane by countering random movements of the car using the flight yoke. The car was manipulated in the 'X' axis, that is left to right in the lane, as is a regular car. To move the car forward in the lane, participants were required to push the steering wheel forward, while pulling back on the steering wheel moved the car back in the lane. The car position was sampled at a rate of 16 hz. Root mean squared (RMS) error was calculated by the following equation:

$$RMS = \sqrt{x^2 + y^2}$$

The lateral deviations and vertical deviations of the car from the target box, were squared, before summing and taking the square root. The RMS value was averaged over the entire five second period immediately after the display task onset for all analyses.

Critical Detection Task. Participants were required to visually scan the roadway and press the brake pedal when a pedestrian icon appeared. The pedestrian remained on the screen until the participant braked or for two seconds if the participant did not respond. Pedestrians appeared on 25% of the trials. On half of these trials, the pedestrian appeared 500 ms after the display task onset. This time value (500 ms) was chosen to ensure that participants were attending to the display prior to switching attention to the road. It is based on the findings of Duncan, Ward, and Shapiro (1994) that once focused, attention remained on an object for about 500 ms before switching to another object. The other half of the pedestrians appeared randomly when no display was presented to ensure temporal uncertainty. Response times were calculated as the difference between the pedestrian onset and the brake response. Missed pedestrians (no response in 10 seconds) were also tabulated.

HUD/HDD Tasks. Two display tasks were presented in the HUD or HDD while participants maintained the tracking task. The display tasks, visual search and verbal-memory, were chosen as they utilize different processing codes, spatial and verbal, respectively (e.g., Baddeley, 1986, 1990).

Visual Search Task. The visual search task utilized in the present study is similar to the task used by Treisman and Gormican (1988) which required participants to search a display of vertical lines and compare line lengths. According to Baddeley (1986, 1990) tasks that represent information in an analog spatial form, as most visual images do, utilize spatial processing codes. Baddeley termed the processing system the "visual spatial scratchpad". The visual search task in the present study was assumed to invoke use of the visual spatial scratchpad and it was intended to evaluate the participants' ability to extract spatial information from complex visual displays. The visual search task approximates the perceptual resources required to determine the location of a pointer in an analog speedometer or fuel gauge.

Participants were asked to identify if a short vertical target line (6.5 mm) was present among a group of identical randomly placed vertical distracter lines

(8 mm) (See Figure 3). All lines were the same colour (green). The target line was present on 1/2 of the trials. Participants were required to press the right hand button if the target line was present and the left button if target was absent. Typically, participants require longer to complete the target absent trials than the target present trials. Two difficulty levels were determined in pilot testing. The easy display contained two lines, whereas the difficult display contained twelve. Participants' response latency (ms) and response accuracy were recorded.

To assess attentional capture in the visual search task, the display-irrelevant condition presented a medium size display that contained eight randomly placed vertical lines. Participants were instructed to ignore the display but maintain the driving and obstacle detection tasks. Thus, no response was required for the visual search task and any presses of the response would be recorded as an error.

Verbal-Memory Task: The present study utilized a modified Sternberg task (e.g. Sternberg 1969, 1975). Typically, in a Sternberg task, participants are presented with a memory set of letters or digits. Subsequently, probe letters are presented and participants are required to report if the probe letter was in the memory set or not. Sternberg (1975) modeled the cognitive processes that are assumed to occur with this task. First, the probe stimulus is encoded, or perceived and given a mental representation. Then the probe representation is compared in series with each member of the memory set. After each serial comparison is completed, a decision is made as to whether a match was found. According to Baddeley (1986, 1990), tasks such as the Sternberg task that represent information in linguistic form, utilize verbal working memory and verbal processing codes. The verbal-memory (Sternberg) task in the present study is thought to approximate the cognitive processes required in automobile displays that employ verbal stimuli, such as digital speedometers and verbal route

Figure 3.
Visual Search Display Task

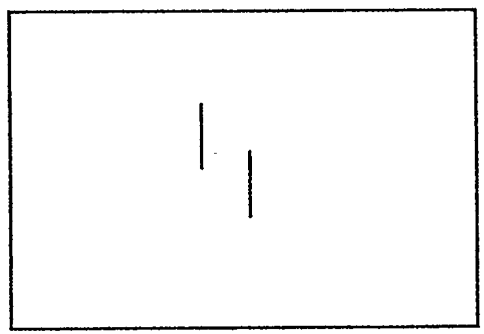


Figure 3a. Easy Visual Search Task
Target-Absent Condition

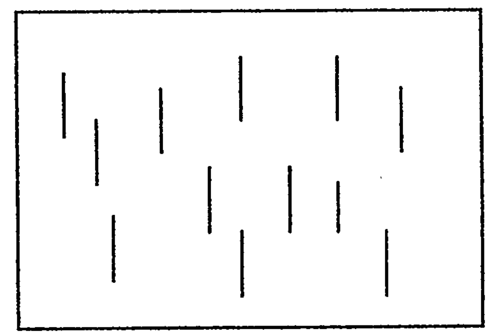


Figure 3b. Difficult Visual Search Task
Target-Present Condition

guidance systems.

The verbal-memory task in the present study was a slightly modified Sternberg task. Prior to each block of trials, participants were given a set of red letters (see Figure 4) which they were asked to memorize. Participants had five seconds to view the memory set, and store it in working memory. They then received a series of three green probe letters. Following each set of test probes, participants were to decide whether any one of the probes was contained in the memory set. When the probe was present in the memory set (target-present), participants were required to press the right response button, mounted on the flight yoke; when absent (target-absent) the left button was the required response. The memory set included a probe letter in 1/2 of the trials. The two difficulty levels, easy (two letter memory set) and hard (five letter memory set), were determined from pilot tests. Participants' response latency (ms) and errors were recorded. Because the task involves serial search, the time to complete the search should increase linearly with the number of items to be searched in the memory set.

To assess attentional capture in the verbal memory display task, display-irrelevant trials presented participants with a memory set of four red letters. Subsequent sets of three green letters, which participants were instructed to ignore, were displayed while participants maintained the tracking and obstacle detection tasks. No response was required for the verbal-memory task, however, tracking performance and braking response times were assessed.

Experimental Design

Testing occurred in two, 90-minute sessions held on separate days with a maximum of three days between sessions. Both sessions began with 30 minutes of training. Using a completely within-subjects design, all participants

Figure 4.
Verbal-Memory Display Task

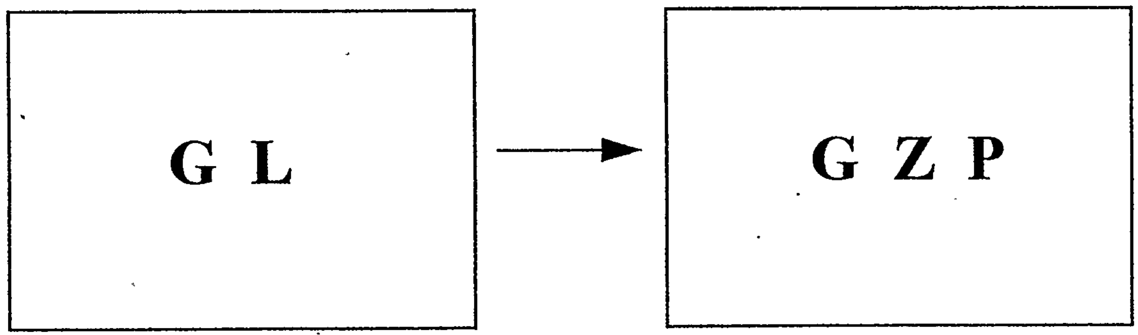


Figure 4a. Easy Verbal-Memory Task
2 Letter Memory Set

Figure 4b. Test Probes
Target-Present Condition

received all combinations of display task (visual search or verbal-memory), display location (HUD or HDD), and display difficulty (easy or difficult). All levels of tracking difficulty, target state, and obstacle state were presented quasi-randomly. The eight participants in each gender group were randomly assigned to receive one of eight orders that were designed to counter-balance the presentation of display tasks, display location, and display task difficulty. One sample experimental order is illustrated in Table 3. A trial, block, set and session are defined below.

Trial. A trial consisted of 14 seconds of continuous tracking in either the easy, medium, or hard condition. The first 7 seconds of each trial consisted of tracking alone, without the presence of a HUD or HDD task. At 7 seconds, the display task (visual search or verbal-memory) appeared and remained present for 5 seconds.

Block. Twelve consecutive trials, of the same display difficulty, were linked together to form a block. Each block lasted 2 minutes and 53 seconds in total; including a 5 second easy tracking warm-up period followed by 12 trials lasting 14 seconds each. The tracking difficulty conditions were presented quasi-randomly. On half of the trials the target was present, in the other half the target was absent. Pedestrian obstacles were randomly presented on three of the 12 trials. Participants were allowed to take a five-minute break after each block.

Set. Six blocks, consisting of two easy display condition blocks, two difficult display condition blocks, and two irrelevant display condition blocks, formed a set. The order of display difficulty was counterbalanced across participants except that all received the display irrelevant conditions last. This allowed participants to habituate to the display. Each set consisted entirely of either HUD trials or HDD trials.

Table 3.
Sample order of experimental trials

Session	Set	Block	Trial 1	2	3	4	5	6	7	8	9	10	11	12
Display Task	Display Location	Display Difficulty	Tracking Difficulty											
Visual Search	HUD	Easy	easy+	easy+	easy-*	easy-	med+**	med+	med-	med-	hard+	hard+	hard-	hard-*
		Easy	easy+	easy+**	easy-	easy-	med+	med+	med-*	med-	hard+**	hard+	hard-	hard-
		Hard	easy+**	easy+	easy-	easy-	med+	med+	med-	med-*	hard+	hard+**	hard-	hard-
		Hard	easy+	easy+	easy-	easy- *	med+	med+**	med-	med-	hard+	hard+	hard-*	hard-
		Ignore	easy+	easy+	easy-*	easy-	med+**	med+	med-	med-	hard+	hard+	hard-	hard-*
		Ignore	easy+	easy+**	easy-	easy-	med+	med+	med-*	med-	hard+**	hard+	hard-	hard-
	HDD	Easy	easy+	easy+	easy-*	easy-	med+**	med+	med-	med-	hard+	hard+	hard-	hard-*
		Easy	easy+	easy+**	easy-	easy-	med+	med+	med-*	med-	hard+**	hard+	hard-	hard-
		Hard	easy+**	easy+	easy-	easy-	med+	med+	med-	med-*	hard+	hard+**	hard-	hard-
		Hard	easy+	easy+	easy-	easy- *	med+	med+**	med-	med-	hard+	hard+	hard-*	hard-
		Ignore	easy+**	easy+	easy-	easy-	med+	med+	med-	med-*	hard+	hard+**	hard-	hard-
		Ignore	easy+	easy+	easy-	easy- *	med+	med+**	med-	med-	hard+	hard+	hard-*	hard-
Verbal-Memory	HUD	Easy	easy+	easy+	easy-*	easy-	med+**	med+	med-	med-	hard+	hard+	hard-	hard-*
		Easy	easy+	easy+**	easy-	easy-	med+	med+	med-*	med-	hard+**	hard+	hard-	hard-
		Hard	easy+**	easy+	easy-	easy-	med+	med+	med-	med-*	hard+	hard+**	hard-	hard-
		Hard	easy+	easy+	easy-	easy- *	med+	med+**	med-	med-	hard+	hard+	hard-*	hard-
		Ignore	easy+	easy+	easy-*	easy-	med+**	med+	med-	med-	hard+	hard+	hard-	hard-*
		Ignore	easy+	easy+**	easy-	easy-	med+	med+	med-*	med-	hard+**	hard+	hard-	hard-
	HDD	Easy	easy+	easy+	easy-*	easy-	med+**	med+	med-	med-	hard+	hard+	hard-	hard-*
		Easy	easy+	easy+**	easy-	easy-	med+	med+	med-*	med-	hard+**	hard+	hard-	hard-
		Hard	easy+**	easy+	easy-	easy-	med+	med+	med-	med-*	hard+	hard+**	hard-	hard-
		Hard	easy+	easy+	easy-	easy- *	med+	med+**	med-	med-	hard+	hard+	hard-*	hard-
		Ignore	easy+**	easy+	easy-	easy-	med+	med+	med-	med-*	hard+	hard+**	hard-	hard-
		Ignore	easy+	easy+	easy-	easy- *	med+	med+**	med-	med-	hard+	hard+	hard-*	hard-

Note: * pedestrain presented 500 ms after display onset
** pedestrian presented randomly when display not present
+ target present
- target absent

Session. One HUD set and one HDD set of the same visual display task (visual search or verbal-memory) constituted a session. The order of display location presentation was counterbalanced across subjects. Four male and four female participants received the visual search task first, and the remaining participants received the verbal-memory task first.

Procedure

Demographic Information. Visual acuity and contrast sensitivity were tested at the beginning of session one. Next, a three-page driving experience questionnaire (see Appendix A) was completed by each participant. Then, the optimal placement of the seat, monitor, steering wheel, and brake pedal was determined by a series of questions. The apparatus was measured to ensure that the distance of the participants' eyes and the monitor was held constant across the two sessions.

Practice and Baseline. The instructional protocol is provided in Appendix D. It provides detailed instructions as presented to the participants. During the first 30 minutes of session one, participants were familiarized with the tracking task and display task (visual search or verbal-memory) to be used that session. The goal of the tracking task and the usage of the steering wheel was explained to participants. Before starting, they were told to press the brake pedal if anything appeared in the roadway and return to the tracking task. Participants practiced the three levels of tracking difficulty as they were presented quasi-randomly throughout three five-minute tracking-alone trials. During the last tracking-alone trial, a pedestrian appeared in the roadway requiring a braking response. This braking response time (BRT) was recorded as the ‘unalerted’ baseline measure.

Participants were then acquainted with the display task location (HUD or HDD) that they were scheduled to receive in set one by completing a minimum of 24 trials of each the easy and difficult display task alone. They were required to achieve 100% accuracy before they could continue. The last six trials for each were recorded for baseline measures of single task performance. Participants then practiced both the tracking task and the display task together for 24 easy and 24 hard trials over 12 minutes of continuous tracking. They were told that a pedestrian may appear any where in the roadway and at any time, and that the correct response is to brake and return to the tracking task as quickly as possible. The importance of keeping the car in the lane and braking for pedestrians was emphasized, and the secondary importance of responding to the visual search/verbal-memory task was noted. That accuracy and response time were both equally important in the display tasks was emphasized to participants.

Session One: Participants received the six blocks of twelve trials each that comprised set one. At the end of the set, participants were permitted a five-minute break. Following the break, participants practiced the display task in the other display location. This time, they completed 12 trials of the easy task alone, and 12 of the difficult task alone. Once 100% accuracy was reached, participants practiced both the tracking task and the display task together for 24 easy and 24 difficult trials over 12 minutes of continuous tracking. Participants then engaged in the second set again consisting of six blocks of 12 trials each. Upon completion of the sessions, participants were thanked and reminded of the date and time of session two.

Session Two. The equipment was set to match individual levels as in session one. Session two began with two five-minute tracking-alone trials to re-familiarize participants with the tracking task. Again, the last tracking-alone trial, included a pedestrian in the roadway, necessitating a braking response. Then, participants were exposed to the second visual display task (visual search or verbal-memory), with the display location being the same as set one in session one. Participants were permitted to practice this task alone, and in combination with the tracking task. Once 100% accuracy and the minimum number of display responses were achieved (as in session one), participants proceeded to the experimental trials and completed set one. Participants repeated the training process for set two and then completed the experimental trials. At the end of the experiment, participants were asked whether they preferred the HUD or the HDD, and were asked to comment further on their experience with HUDs.

Results

Preliminary omnibus analyses of variances (ANOVA) revealed no significant gender effects or order effects (HUD/HDD first or second), therefore reported analyses are collapsed across these variables. The data were analyzed with repeated-measures ANOVAs incorporating the Greenhouse-Geisser correction for violations of sphericity where appropriate, a significance level of .05 is reported throughout. Line graphs were used throughout as they better illustrated the effects, however, some variables were categorical in nature. Baseline observations, visual search task analyses, verbal-memory task analyses, and sample characteristics analyses are presented separately.

Baseline Observations

Prior to the first experimental session, baseline measures were taken to assess single task performance for the tracking task, visual search latency, and verbal-memory latency (see Table 4). In addition, one obstacle braking

Table 4.

Baseline measurements for single task trials

Task	Task Difficulty	Target State	Mean	SD
Tracking (RMS)	Easy	N/A	31.27	2.36
	Medium	N/A	34.11	3.56
	Difficult	N/A	38.33	5.20
Visual Search Task Latency (ms)	Easy	Present	715.47	124.10
		Absent	751.64	112.13
	Difficult	Present	1277.17	354.73
		Absent	1693.22	452.61
Verbal-Memory Task Latency (ms)	Easy	Present	893.93	287.07
		Absent	1075.39	230.84
	Difficult	Present	1188.67	282.41
		Absent	1581.39	375.19

response time (BRT) was collected from each participant during a tracking only baseline trial (i.e. no visual search or verbal-memory task). The mean time for the first pedestrian presented (M = 1121 ms) can be compared to a mean of the remaining pedestrian BRTs (M = 1019.5 ms). As would be expected, the surprise element was reduced over the experimental trials, thus BRTs were shorter.

Visual Search Task Sessions

The visual search task presented in the HUD and HDD required participants to determine if one of a set of two or twelve vertical lines was shorter than the others. The visual search task was completed while maintaining tracking performance and braking for critical events (pedestrians) on the simulated roadway. Analyses of tracking performance, visual search task latency, critical event detection, and attentional capture from the visual search sessions will be presented.

Tracking Performance

Tracking performance was assessed for the interval during which the visual search task was presented (See Table 5). Pedestrians appeared 500 ms after the onset of quasi-randomly selected visual search tasks. However, pedestrians only appeared when the target (short-line) did not appear in the visual search task (i.e. target-absent trials). This necessitated the participants to scan the entire display ensuring that they were attending to the display at the time of the pedestrian onset. Therefore, the effects of target state and pedestrian state on tracking performance were analyzed separately.

Table 5.
Means and Standard Deviations for Tracking Performance with the Visual Search Task.

A) Tracking Performance: No Pedestrian Trials

Factor	Level	Mean	SD
Display Location	HUD	34.41	4.34
	HDD	35.27	4.85
Visual Search Task Difficulty	Easy (2 lines)	34.89	4.15
	Difficult (12 lines)	34.78	5.05
Target State	Present	34.97	4.34
	Absent	34.71	4.88
Tracking Difficulty	Easy	31.16	2.44
	Medium	34.94	3.33
	Difficult	38.42	4.54

B) Tracking Performance: Target-Absent Trials

Factor	Level	Mean	SD
Display Location	HUD	34.93	5.71
	HDD	35.65	6.57
Visual Search Task Difficulty	Easy (2 lines)	35.23	5.75
	Difficult (12 lines)	35.35	6.55
Pedestrian State	Present	35.87	7.17
	Absent	34.17	4.88
Tracking Difficulty	Easy	31.44	4.81
	Medium	35.25	4.48
	Difficult	39.19	6.38

Note:
A) No pedestrian trials; No pedestrians appeared during the visual search task presentation.

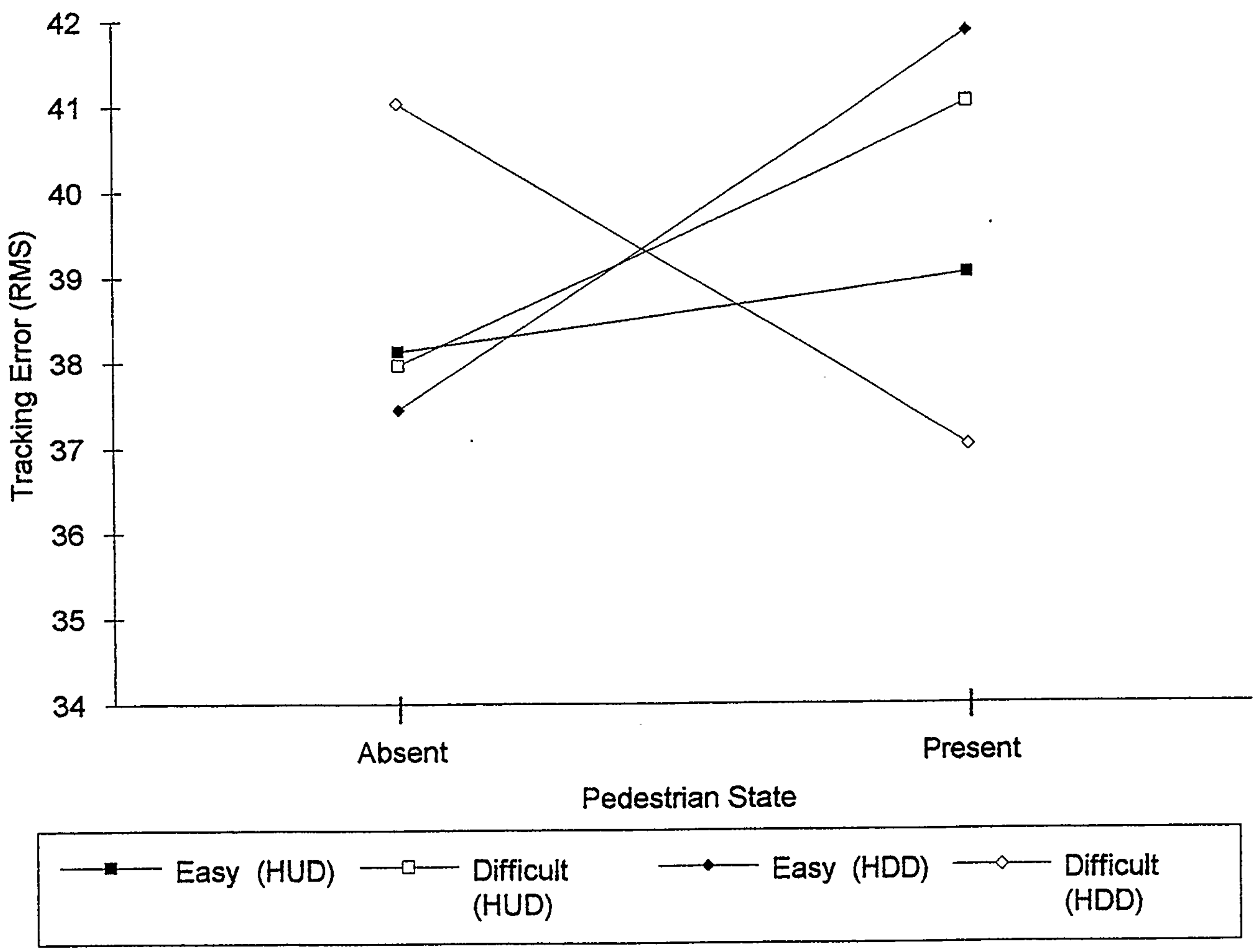
B) Target absent trials; The short target line was not present in the visual search task.

A) Tracking Error: No Pedestrian Trials. A 2 (display location) X 2 (visual search task difficulty) X 2 (target state) X 3 (tracking difficulty) repeated measures ANOVA was performed on the tracking RMS error data. Increased tracking difficulty increased RMS error, $F(2,30)=111.37$, $p=.000$. Post-hoc Tukey HSD tests indicated significant differences among all levels of tracking difficulty ($p<.05$). No interactions were significant, indicating that tracking performance was not affected by the location or difficulty of the visual search task when the pedestrian did not appear on the road. This was likely because of the high priority placed on the tracking task.

B) Tracking Error: Target-Absent Trials. A 2 (display location) X 2 (visual search difficulty) X 3 (tracking difficulty) X 2 (obstacle state) repeated measures ANOVA was performed on the RMS data to assess tracking performance with and without the presence of the pedestrian. A significant main effect of tracking difficulty, $F(2,30)=125.84$, $p=.0000$, was found and post-hoc Tukey HSD tests revealed significant differences among all levels ($p<.05$). There was a significant main effect of pedestrian state, $F(1,15)=4.68$, $p=.04$, which meant that tracking error was higher when the pedestrian was present. This is plausible because attention was likely diverted to the pedestrian and away from the tracking task.

A four-way interaction (display location X visual search task difficulty X tracking difficulty X pedestrian state) was also observed ($F(2,30)=6.27$, $p=.0053$). Simple effects tests were conducted to examine the three way interaction (display location X visual search difficulty X pedestrian state) at each level of tracking difficulty. A significant three-way interaction was found in the difficult tracking condition only ($F(1,15)=12.11$, $p<.0034$). As illustrated in Figure 5, tracking error increased with the presence of the pedestrian in all conditions except the HDD/difficult visual search task condition, where tracking error

Figure 5. Tracking Error as a Function of Display Location, Visual Search Task Difficulty and Pedestrian State within the Difficult Tracking Condition



actually decreased. Post hoc Tukey HSD tests revealed that in the high workload situations (difficult tracking, difficult visual search task), requiring a braking response to a pedestrian, tracking error was higher with the HUD than the HDD. This may have occurred because the attention demanded by the task exceeded the participants' capacity. However, in the same high load condition, when there was no pedestrian to respond to, tracking error was higher with the HDD. This makes sense, as in order to answer the difficult visual search task, participants had to take their eyes off the road for longer periods of time, thereby affecting their driving performance.

Visual Search Task Latency

Each subject was required to maintain 90% accuracy in determining whether the short target line was present or not; the mean overall accuracy rate was 95.77%. One participant neglected to make a response on one of the visual search tasks. This represented less than .07% of the data. This point, in addition to one other data point three standard deviations above the mean, was replaced with the group mean for the trial, on the assumption that it represented a momentary lapse of attention by the observer. The means and standard deviations for the visual search task latency are found in Table 6. Because pedestrians were only presented on target-absent trials (i.e. when the short target line was not present in the visual search task), the effect of target state and pedestrian state were analyzed separately.

A) Visual Search Task Latency: No Pedestrian Trials. A 2 (display location) X 2 (visual search task difficulty) X 2 (target state) X 3 (tracking difficulty) repeated measures ANOVA was performed on the visual search task latency data for all trials for which no braking response was required. On average, visual search latency was shorter (302 ms) when presented in the HUD

Table 6.

Means and Standard Deviations for Visual Search Latency

A) Visual Search Latency: No Pedestrian Trials

Factor	Level	Mean (ms)	SD
Display Location	HUD	1516.39	39.01
	HDD	1818.44	53.77
Visual Search Task Difficulty	Easy (2 lines)	1269.69	26.67
	Difficult (12 lines)	2065.14	47.79
Target State	Present	1533.01	38.63
	Absent	1801.82	54.49
Tracking Difficulty	Easy	1620.79	57.34
	Medium	1639.64	54.25
	Difficult	1741.81	64.78

B) Visual Search Latency: No Target Trials

Factor	Level	Mean (ms)	SD
Display Location	HUD	1920.81	67.82
	HDD	2143.09	76.81
Visual Search Task Difficulty	Easy (2 lines)	1438.61	45.51
	Difficult (12 lines)	2625.29	69.79
Pedestrian State	Present	2262.07	84.29
	Absent	1801.83	54.50
Tracking Difficulty	Easy	1884.76	84.58
	Medium	1994.30	82.99
	Difficult	2216.79	97.38

Note:
A) No pedestrian trials; No pedestrians appeared during visual search task.
B) Target-absent trials; The short line was not present in the visual search task.

than the HDD, $F(1,15)=471.99$, $p=.0002$, indicating that significantly less visual search time was required to extract information from the HUD, than the HDD. Visual search latency was significantly shorter for the easier (two line) condition than for the difficult (twelve-line) condition ($F(1,15)=93.81$, $p=.0000$), as there were fewer items to search. Latency was significantly faster when the target line was present than when it was absent ($F(1,15)=19.63$, $p=.0005$). This presumably occurred because the serial search was terminated upon target detection on target-present trials, obviating the need to search the entire display. There was a significant main effect for tracking difficulty, $F(2,30)=4.36$, $p=.0218$, however, post-hoc Tukey HSD tests revealed no significant differences among the levels.

These main effects of display location, visual search task difficulty, target state, and tracking difficulty must be interpreted with caution given the presence of interactions among them. A visual search task difficulty by target state interaction was found ($F(1,15)=8.63$, $p=.0102$) (see Figure 6). Simple effects tests were significant for both the target within the easy (two line) condition, $F(1,15) = 9.61$, $p=.0073$ and for the target within the difficult (twelve line) condition, $F(1,15) = 18.46$, $p=.000$. An examination of the means indicated that the difference between the target-absent and target-present condition was much greater with the difficult visual search task, than the easy task. This is because when the short line was not present in the easy condition, only two lines had to be searched to make a decision. However, in the difficult condition, twelve lines had to be searched serially, to determine that none of them was the short line.

There was also a visual search task difficulty by tracking difficulty interaction ($F(2,30) = 5.75$, $p=.0077$) (see Figure 7). Visual search latencies were not affected by tracking difficulty in the easy visual search task, but they did increase with tracking difficulty in the difficult visual search task ($F(2,30) =

Figure 6. Visual Search Latency as a Function of Visual Search Task Difficulty and Target State

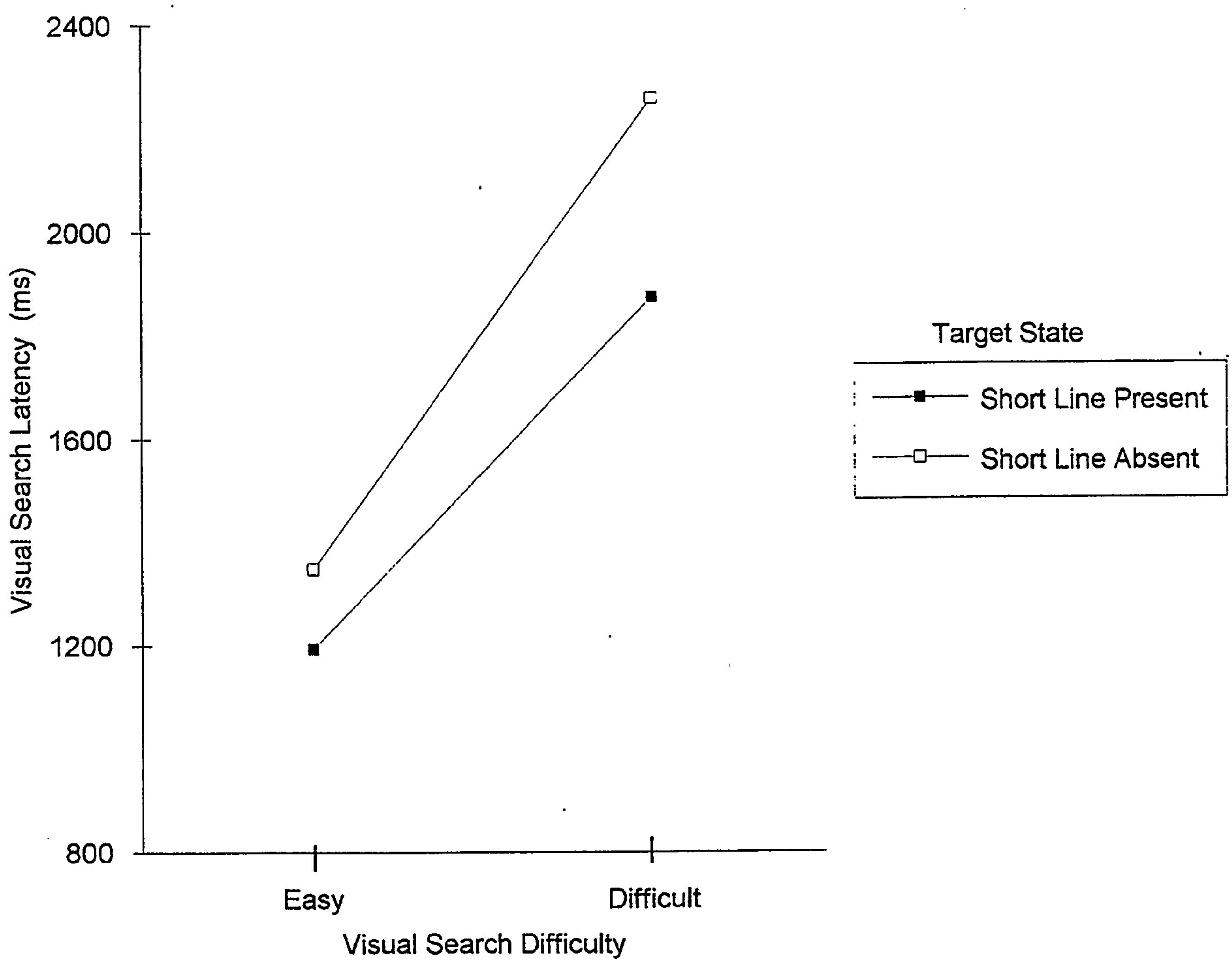
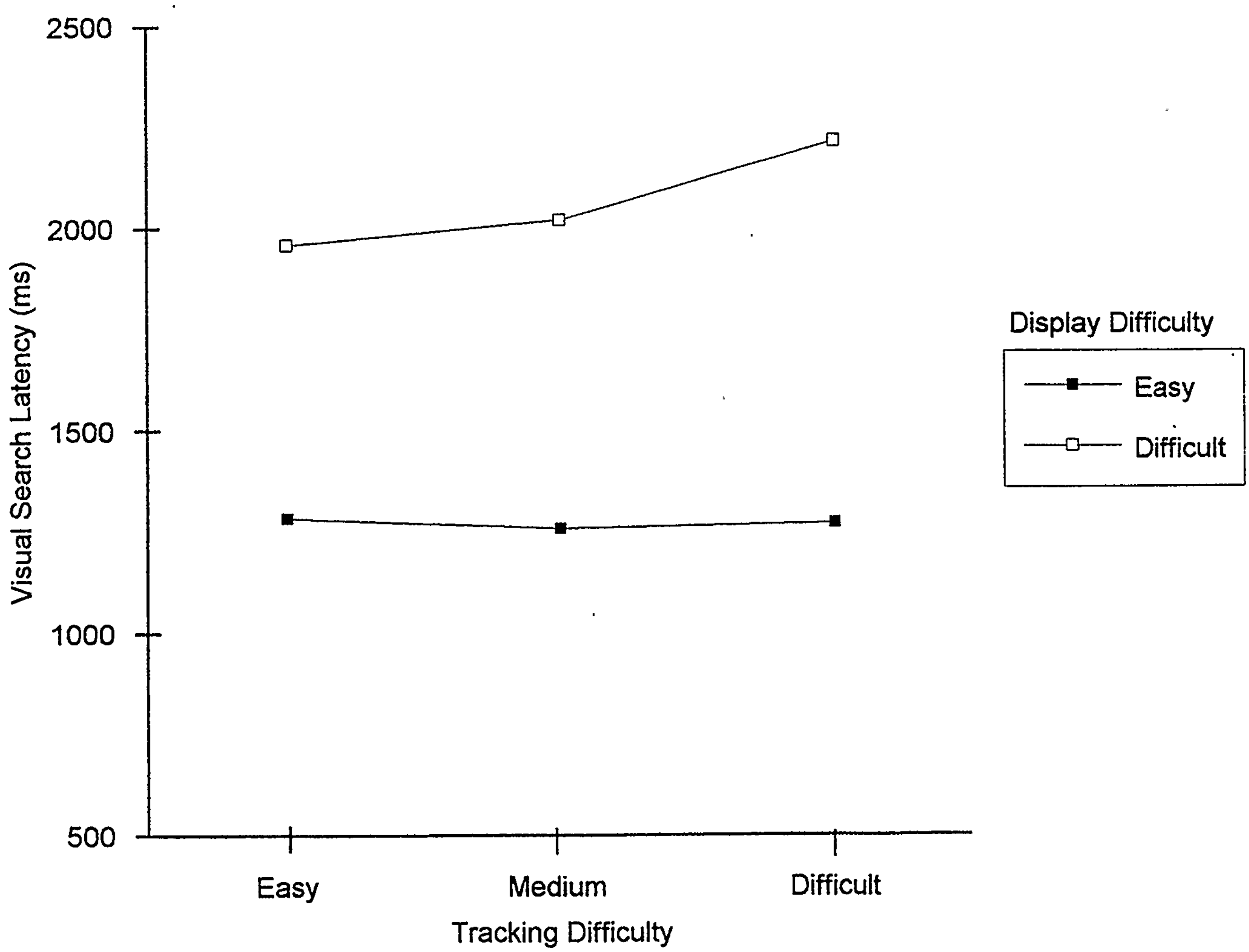


Figure 7. Visual Search Latency as a Function of Tracking Difficulty and Visual Search Task Difficulty

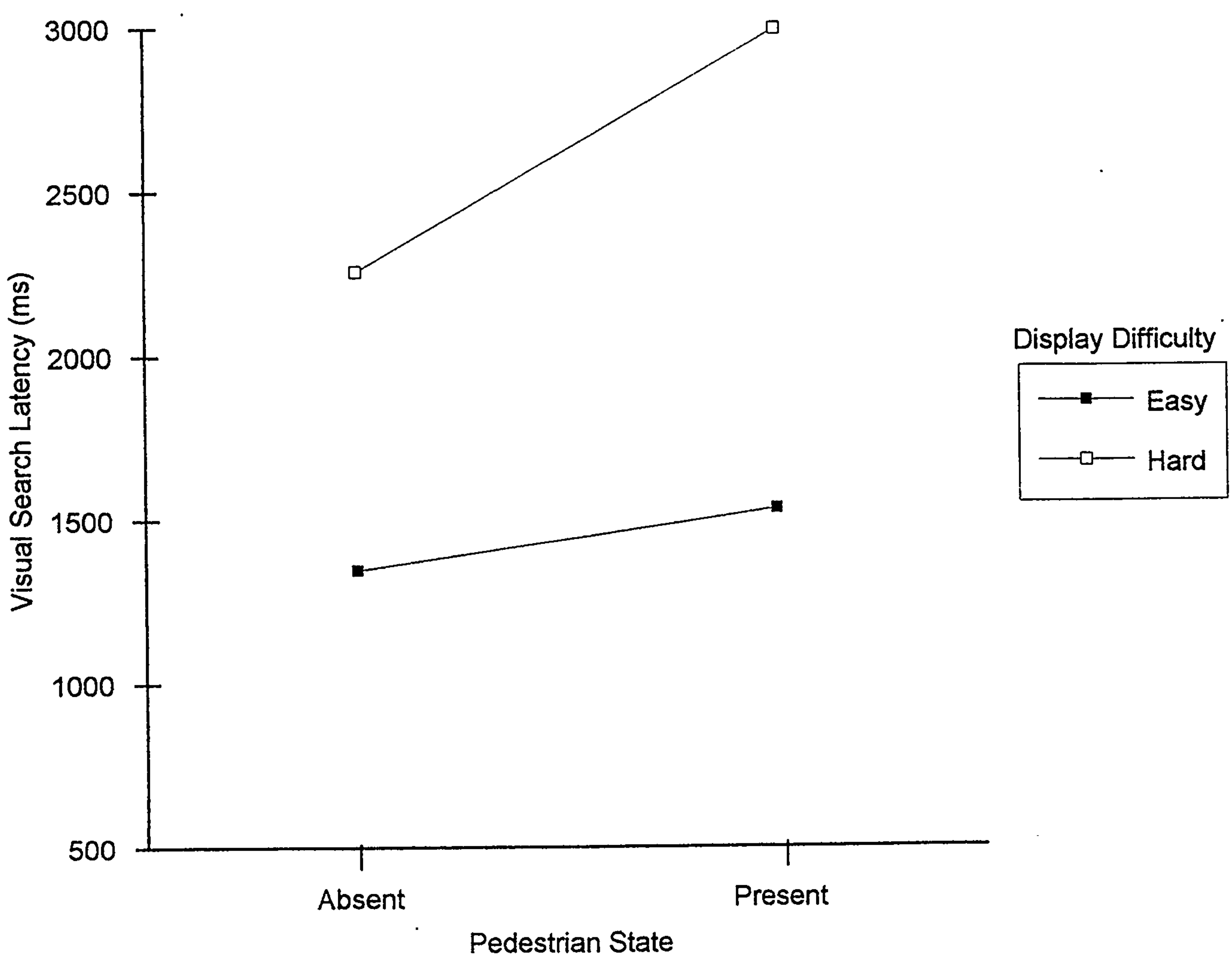


9.20, p=.0008). Significant differences between the easy and difficult tracking conditions, and the medium and difficult tracking conditions, (p <.05), reflected a decrement in performance associated with higher workload.

B) Visual Search Task Latency: Target-Absent Trials. A 2 (display location) X 2 (visual search task difficulty) X 3 (tracking difficulty) X 2 (pedestrian state) repeated measures ANOVA was conducted to examine the effect of the pedestrian on visual search latency. A main effect for display location, $F(1, 15)=10.24$, $p=.006$, indicated that visual search latencies were faster with the HUD than the HDD. The difference (222.28 ms) is comparable to the time required to complete a visual saccade. The main effect for visual search task difficulty, $F(1,15)=111.37$, $p=.000$, showed that visual search latencies were faster for the easy two line condition than the difficult twelve line condition, again presumably because the easy display required serial search of fewer lines (two) than the difficult display with twelve lines. A tracking difficulty main effect, $F(2,30)=9.03$, $p<.0009$, was also observed, indicating that visual search latencies increased as tracking difficulty increased. Further, a main effect for pedestrian state was obtained ($F(1,15)=28.09$, $p=.0001$). Slower display response times were found when the pedestrian was present. These results suggest that participants followed the instructions to drive and brake for pedestrians as their first priority, and to respond to the visual search task once they were in control of the driving situation.

The above main effects must be interpreted with caution, however, due to the presence of interactions. There was a significant visual search task difficulty by pedestrian state interaction ($F(1,15)=22.29$, $p= .0003$) (see Figure 8). Simple effect tests suggest that in the easy, two line condition, visual search latency did not differ significantly with the presence of the pedestrian, but in the difficult twelve line condition, visual search latency was significantly longer when the

Figure 8. Visual Search Latency as a Function of Visual Search Task Difficulty and Pedestrian State



pedestrian was present. Apparently participants could successfully brake and respond to the visual search task simultaneously in the easy condition, but had more difficulty performing in the difficult condition.

A tracking difficulty by pedestrian state interaction was also significant ($F(2, 30)=3.51$, $p=.0426$) (see Figure 9). Simple effects tests revealed that visual search latencies were slowed by the presence of the pedestrian in the easy ($F(1,15)=5.17$, $p=.0382$), medium ($F(1,15)=18.26$, $p=.0007$), and difficult ($F(1,15)=19.73$, $p=.0005$) tracking conditions with the effect being greater as tracking difficulty increased. Again, participants appeared to follow instructions to prioritize driving and braking for pedestrians such that demands of the tracking task increased the latency of the visual search task responses.

Pedestrian Braking Response Times (BRTs)

In each set of trials, half of the pedestrians appeared in the roadway 500 ms after the onset of the visual search task, and half appeared randomly when the visual search task was not present. The latter served as a control measure to determine if braking response time was affected by the presence of the visual search task. Overall, BRTs in the control condition (i.e. no visual search task) ($M = 957.59$) were significantly faster than when braking responses were required simultaneously with the visual search task ($M=1078.43$), ($F(1,15)=21.52$, $p=.0003$). This shows that presenting information in the displays (HUD or HDD) slowed BRTs to critical events in the roadway.

BRTs were analyzed using a 2 (display location) X 2 (display difficulty) X 3 (tracking difficulty) repeated measures ANOVA for pedestrians that appeared 500 ms after the onset of the target-absent visual search task (see Table 7). This analysis assessed attentional switching from the display to the roadway. Participants braked faster ($F(1,15)=5.34$, $p=.0355$) using the HUD

Figure 9. Visual Search Latency as a Function of Tracking Difficulty and Pedestrian State

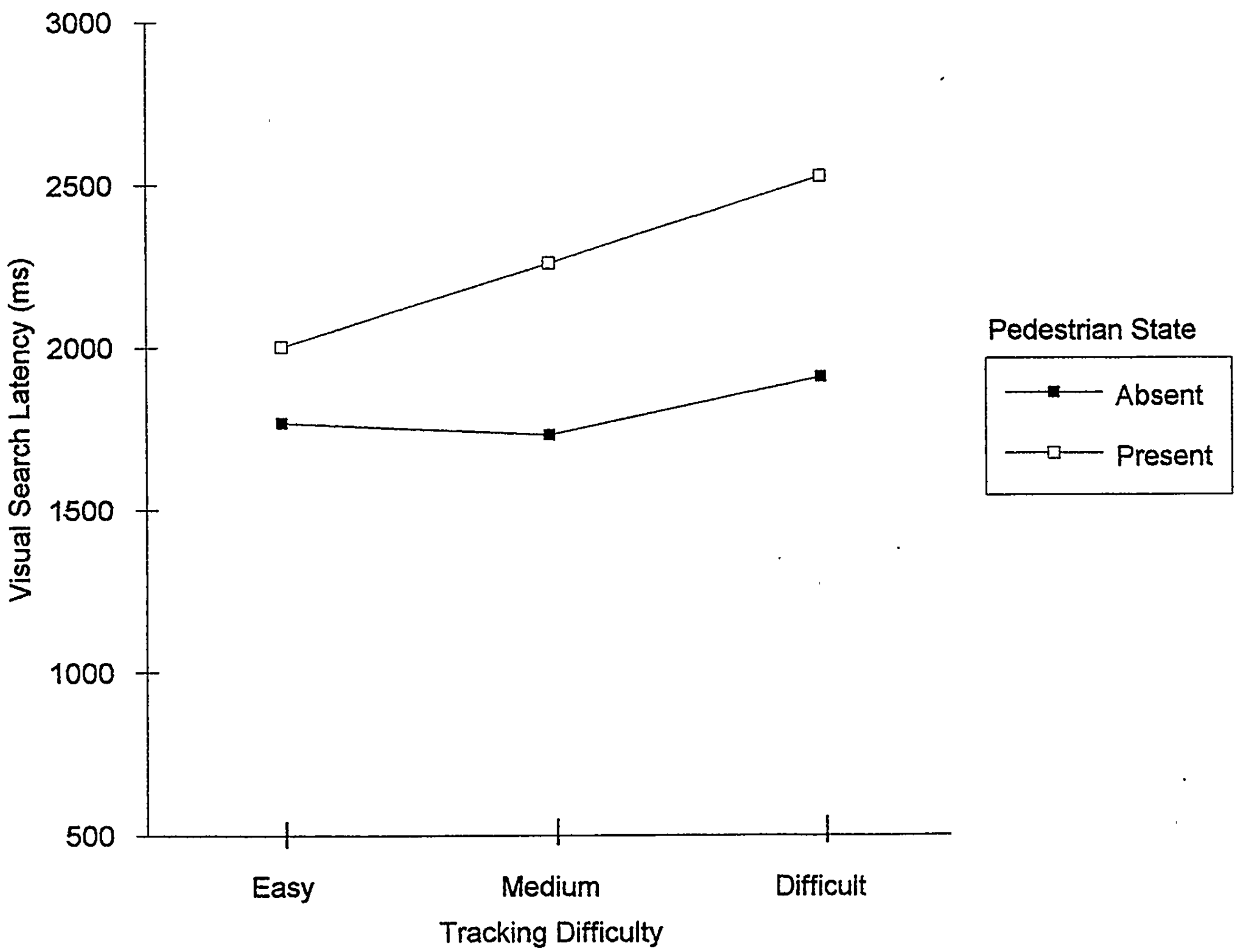


Table 7.

Means and Standard Deviations for Braking Response Times to Pedestrians with the Visual Search Task.

Factor	Level	Mean (ms)	SD
Display Location	HUD	1023.93	191.66
	HDD	1132.94	339.66
Visual Search Task Difficulty	Easy (2 lines)	1089.17	242.14
	Difficult (12 lines)	1067.70	315.03
Tracking Difficulty	Easy	1021.58	254.74
	Medium	1050.34	245.71
	Difficult	1163.38	318.95

than the HDD, however, both were slower than the control condition (no visual search task), $p<.05$, (see Figure 10). It appears that participants took less time to return their attention to the tracking task after responding to the visual search task in the HUD than the HDD, presumably due to the time required to move the eyes or attention from the HDD to the simulated roadway. BRTs were also affected by tracking difficulty, $F(2, 30)=17.26$, $p=.0000$. Post hoc Tukey HSD tests indicated that BRTs were shorter in the easy than the difficult tracking condition ($p<.05$), likely due to the lighter demands of the tracking task. None of the interactions was significant.

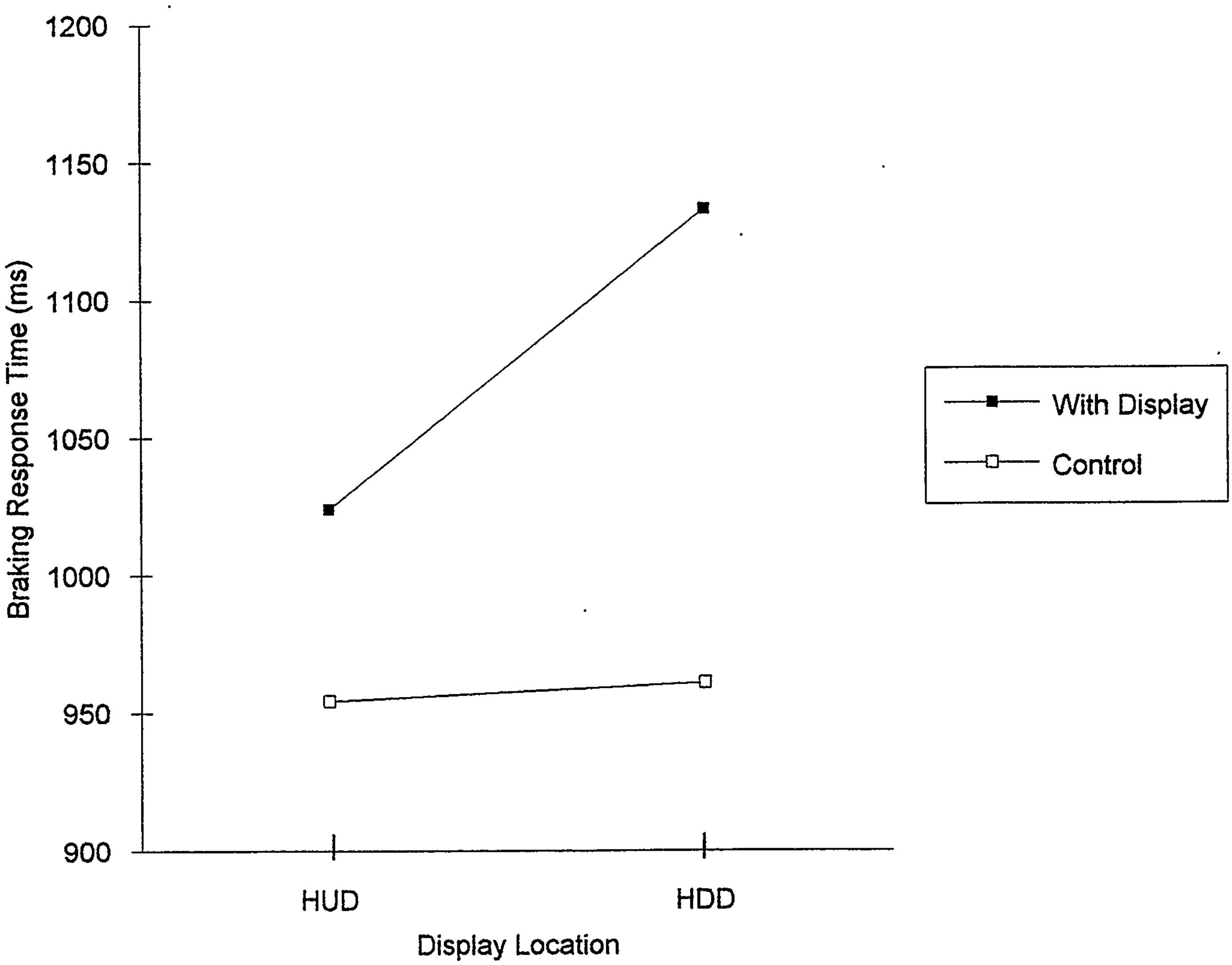
Attentional Capture

In the two attentional capture blocks at the end of each set, display-irrelevant trials were presented in which participants were instructed to ignore the visual search task presented in either the HUD or the HDD. Tracking and braking performance were assessed.

A 2 (Display Location) X 2 (Pedestrian State) X 3 (Tracking Difficulty) repeated measures ANOVA was conducted on the tracking performance (RMS error) data. Tracking did not differ significantly as a function of the location of the display-irrelevant (visual search) task ($F(1,15)=1.83$, $p=.1962$). Therefore, there was no difference in tracking performance if the irrelevant visual search task was presented in the visually salient HUD, that was close to the central tracking task, or of it was presented in the HDD, below the normal line of sight.

To assess attentional capture in each of the HUD and HDD sets, twelve pedestrians were presented; six 500 ms after the onset of the irrelevant visual search task, and six without the visual search task. The latter constituted the control measure. One BRT data point was removed from the analysis because it was more than three standard deviations above the mean, in the direction of a

Figure 10. Braking Response Times as a Function of Visual Search Display Location



slower BRT. Although it may be of importance to determine the cause of the delayed BRT, it was discarded as an outlier in the analyses.

The HUD and HDD control BRTs (i.e. no display present) were compared (see Table 8) as a manipulation check and as expected no significant differences were detected ($F(1,15)=0.07$, $p=.7986$). Next, the hypothesis that the irrelevant display would slow BRTs relative to control BRTs was tested (see Figure 11). In the HUD-irrelevant condition, BRTs did not differ significantly from the control BRTs ($F\ (1,15)=0.29$, $p=.5983$). This indicated that the irrelevant HUD display did not affect braking performance. Similarly, BRTs in the HDD-irrelevant condition were not significantly different than the control condition ($F=(1,15)=0.22$, $p=.6484$). That BRTs were not slowed by the presence of either the HUD or the HDD suggests that participants' attention was not captured by either display, at least to the extent that performance suffered. Finally, to test the hypothesis that the visual salience of the HUD would create attentional capture more so than the HDD, BRTs in the display-irrelevant condition were compared for the presence of a display location effect; none was detected ($F(1,15)=0.39$, $p=.5440$). Therefore, there was no evidence to suggest that the irrelevant HUD captured the participants' attention more than the irrelevant HDD.

Summary

The results of the visual search display task analyses revealed that tracking performance deteriorated with HUD use in conditions of high mental workload that required a braking response. Tracking performance deteriorated with the HDD, presumably due to eye movements, in high workload conditions where no braking response was required. A slight HUD advantage was found for visual search task latencies. Critical event BRTs were slightly faster with the HUD than the HDD, however, both were slower than the control (no display)

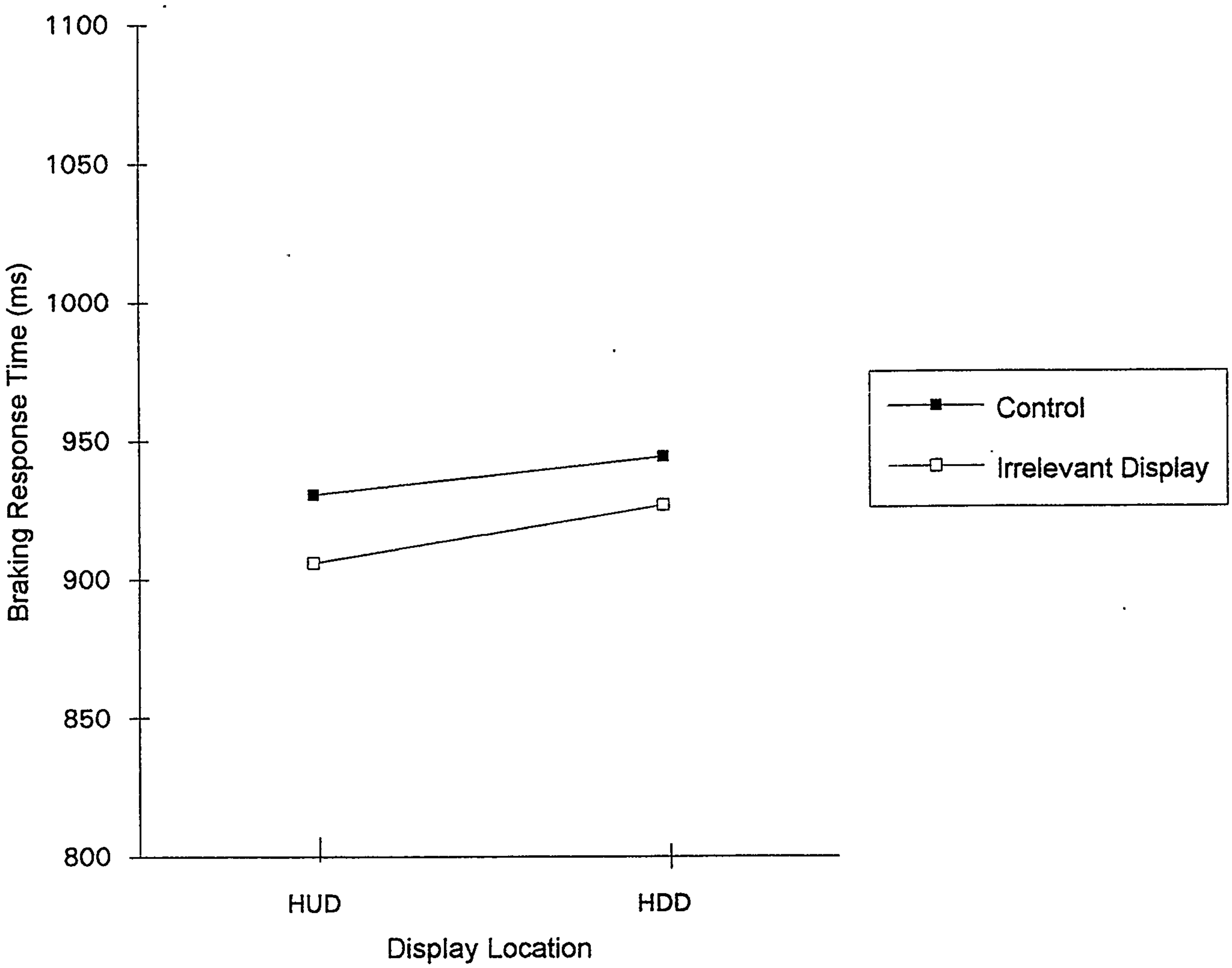
Table 8.

Means and Standard Deviations for Braking Response Times for the Visual Search Task Irrelevant Trials.

Display	Mean (SD) Braking Time (ms)		Mean Difference
Location	No Display (Control)	Irrelevant Display	No Display - Display
HUD	930.57 (286.15)	905.81 (156.09)	24.76
HDD	944.35 (225.03)	926.53 (309.65)	17.82
HDD - HUD	13.78	20.72	

Note: There were no significant differences between any of the means.

Figure 11. Braking Response Time with the Irrelevant Visual Search Task



BRTs. Finally, there was no evidence to suggest that participants' attention was captured by the HUD (or HDD) in the display-irrelevant trials.

Verbal-Memory Task Sessions

Results from the verbal-memory task sessions, which required participants to determine if probe letters were among a memory set of letters, are described in four subsections; tracking performance, verbal memory task latency, critical event detection, and attentional capture.

Tracking Performance

Tracking performance (RMS error) was assessed for the interval during which the verbal-memory task was presented (See Table 9). Pedestrians appeared 500 ms after the onset of quasi-randomly selected verbal-memory tasks. However, pedestrians only appeared when the target (probe letter) did not appear in the memory set (i.e. target-absent trials). This necessitated the participants to compare the memory set with all letters in the entire display; ensuring that they were attending to the display at the time of the pedestrian onset. Therefore, the effects of target state and pedestrian state on tracking performance were analyzed separately.

A) Tracking Performance: No Pedestrian Trials. A 2 (display location) X 2 (verbal-memory task difficulty) X 2 (target state) X 3 (tracking difficulty) repeated measures ANOVA was performed on the RMS data. There was a significant main effect of tracking difficulty ($F(2,30)=121.82$, $p=.0000$). Post hoc Tukey HSD tests revealed significant differences between the easy and difficult conditions, and the medium and difficult conditions, ($p<.05$).

Table 9.

Means and Standard Deviations for Tracking Performance with the Verbal-Memory Task

A) Tracking Performance: No Pedestrian Trials

Factor	Level	Mean	SD
Display Location	HUD	35.41	4.66
	HDD	35.35	4.99
Verbal-Memory Task Difficulty	Easy (2 letters)	35.17	4.93
	Difficult (5 letters)	35.60	4.71
Target State	Present	35.45	4.93
	Absent	35.31	4.71
Tracking Difficulty	Easy	31.80	2.61
	Medium	34.80	3.39
	Difficult	39.54	4.59

Tracking Performance: No Target Trials

Factor	Level	Mean	SD
Display Location	HUD	36.07	6.75
	HDD	36.59	7.87
Verbal-Memory Task Difficulty	Easy (2 letters)	36.44	7.37
	Difficult (5 letters)	36.22	7.29
Obstacle Presence	Present	37.36	9.01
	Absent	35.31	4.93
Tracking Difficulty	Easy	31.68	4.47
	Medium	35.93	6.09
	Difficult	41.38	7.56

Note:

A) No pedestrian trials; No pedestrians appeared during verbal-memory task presentation.

B) Target-absent trials; Test probes were not contained in the memory set

A verbal-memory task difficulty by target state by tracking difficulty interaction, $\underline{F}(2,30)=3.92$, $\underline{p}=.0307$, was observed. Simple effect tests revealed significant two way interactions; verbal memory task difficulty by target state, within both the easy tracking condition, $\underline{F}(1,15)=5.87$, $\underline{p}=.0286$ and difficult tracking condition, $\underline{F}(1,15)=6.79$, $\underline{p}=.0198$, but not the medium tracking condition. Figure 12 represents the verbal-memory difficulty by target state interaction within the easy tracking condition. Post hoc Tukey HSD tests revealed that in the target-absent condition (i.e. the probe letters were not in the memory set), tracking error was not affected by verbal-memory task difficulty, whereas, in the target-present condition (i.e. the one probe letter was in the memory set), tracking performance deteriorated in the harder (5 letter memory condition. The verbal-memory task difficulty by target state interaction within the difficult tracking condition is illustrated in Figure 13. In the target absent condition, tracking performance was not affected by the difficulty of the verbal-memory task. However, in the target present condition, tracking performance was worse in the easier (two letter memory set) condition than the harder (five letter memory set) condition ($p<.05$).

B) Tracking Performance: Target-Absent Trials. A second analysis, a 2 (display Location) X 2 (verbal-memory task difficulty) X 3 (tracking difficulty) X 2 (obstacle state) repeated measures ANOVA, was performed on the RMS error data to allow a comparison between tracking performance with and without the presence of the pedestrian. A significant main effect for tracking difficulty was found ($\underline{F}(2,30)=71.53$, $\underline{p}=.0000$). Subsequent Tukey HSD tests revealed significant differences between the easy and difficult, and the medium and difficult, levels of tracking ($\underline{p}< .05$). Also, there was a significant main effect of pedestrian state ($\underline{F}(1,15)=5.61$, $\underline{p}=.0317$). Tracking error was higher when the pedestrian was present than when it was not, likely because task demands were higher with the pedestrian than without. No interactions were significant.

Figure 12. Tracking Error as a Function of Verbal-Memory Task Difficulty and Target State in the Easy Tracking Condition

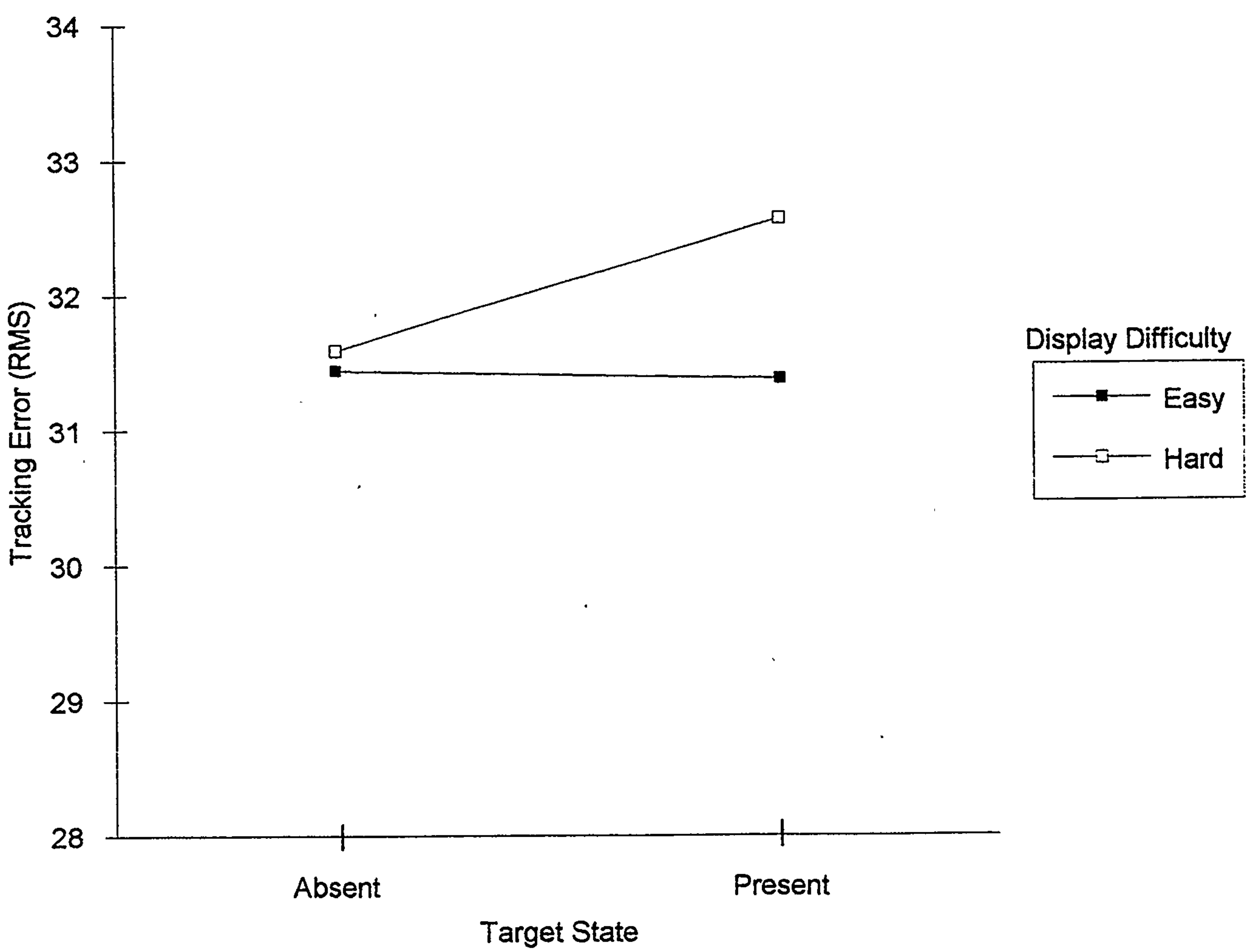
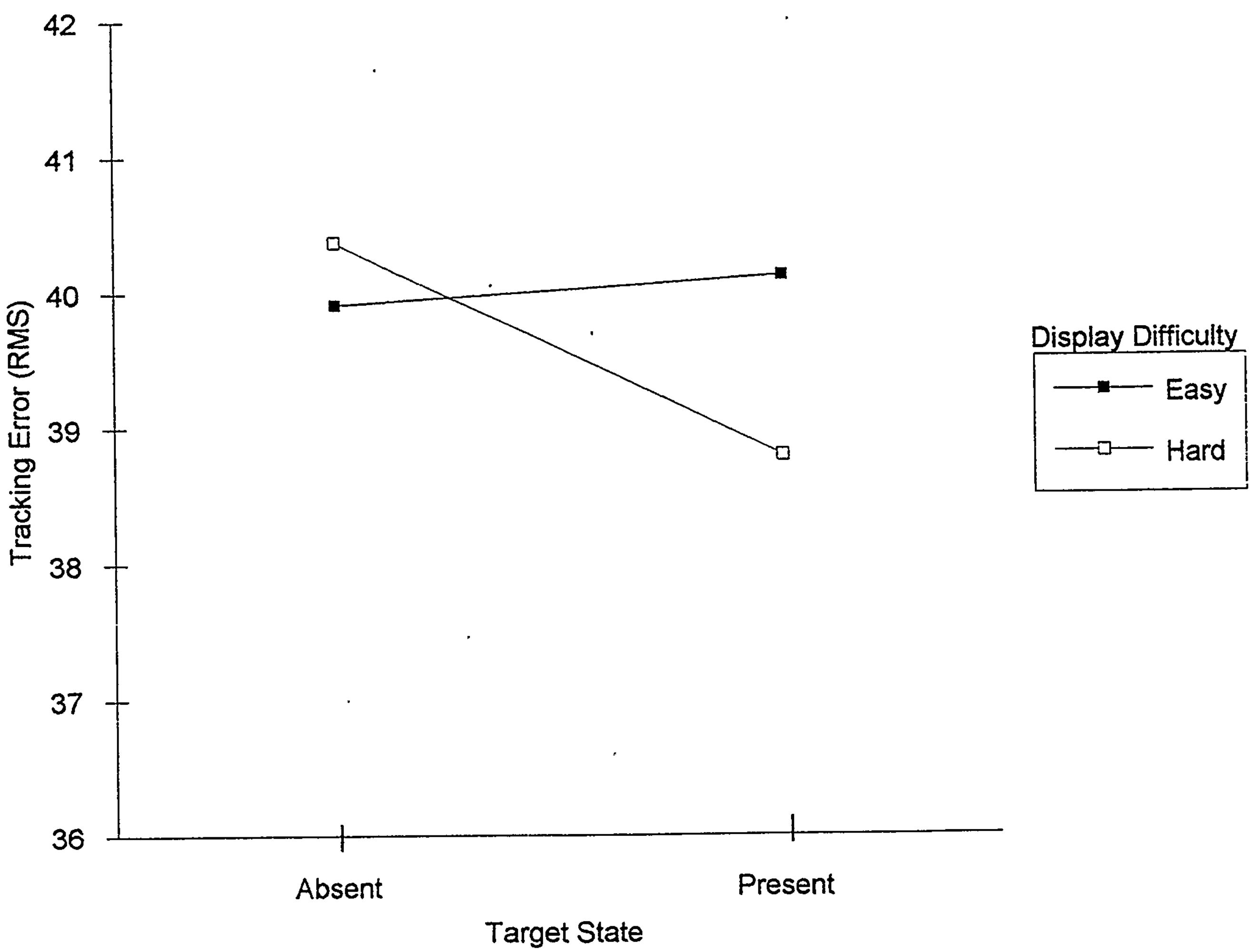


Figure 13. Tracking Error as a Function of Verbal-Memory Task Difficulty and Target State in the Difficult Tracking Condition



Tracking was not affected by the location or difficulty of the verbal-memory display task. This could have occurred because participants placed the tracking task at a higher priority than the verbal-memory display task. Alternatively, it could be that attentional resources were shared between the verbal-memory task such that tracking performance did not suffer.

Verbal-Memory Task Latency

The number of correct responses to the verbal-memory task were calculated to ensure that each subject maintained 90% accuracy. The overall mean accuracy rate with which participants were able to determine if the probe set did or did not contain any of the memory set letters was 93.62%. In no case did participants neglect to respond to the display tasks. The means and standard deviations for the verbal-memory task latencies are found in Table 10. As with the visual search task, pedestrians only appeared during trials in which the target was absent to control for the variability of where the target was presented within the display (i.e., only when the test probes were not in the memory set). Therefore, the effects of target and pedestrian state on verbal-memory latency were analyzed separately.

A) Verbal-Memory Task Latency: No Pedestrian Trials. A 2 (display location) X 2 (verbal-memory task difficulty) X 2 (target state) X3 (tracking difficulty) repeated measures ANOVA was performed on the verbal-memory task latencies for trials on which no obstacle was presented. There was a significant display location effect ($F(1, 15)=10.96$, $p=.0048$), with response times faster when the information was presented in the HUD. The time difference (171.68 ms) approximates an eye movement. Response times were significantly faster for the easy, two letter memory set condition, than the difficult, five letter memory set condition ($F(1, 15)=61.38$, $p=.0000$). Presumably, this occurred because the

Table 10.

Means and Standard Deviations for Verbal-Memory Latency

A) Verbal Memory Latency: No Pedestrian Trials

Factor	Level	Mean (ms)	SD
Display Location	HUD	1576.45	510.64
	HDD	1748.13	618.61
Verbal-Memory Task Difficulty	Easy (2 letters)	1449.91	445.89
	Hard (5 letters)	1874.68	607.46
Target State	Present	1515.60	508.17
	Absent	1808.60	597.28
Tracking Difficulty	Easy	1677.75	576.86
	Medium	1612.76	546.59
	Difficult	1696.37	595.44

B) Verbal-Memory Latency: Target-Absent Trials

Factor	Level	Mean (ms)	SD
Display Location	HUD	2037.69	820.52
	HDD	2115.17	855.34
Verbal-Memory Task Difficulty	Easy (2 letters)	1808.71	751.69
	Difficult (5 letters)	2344.16	835.91
Obstacle Presence	Present	2343.88	952.54
	Absent	1808.98	597.28
Tracking Difficulty	Easy	2065.69	816.31
	Medium	2017.88	783.16
	Difficult	2145.72	910.63

Note:
A) No pedestrian; No pedestrians appeared during verbal-memory display presentation.

B) Target-absent trials; Test probe was not contained in the memory set easy condition only required two mental comparisons of the probe letters to the memory set, where as five were required in the difficult condition. A significant target state effect was also noted ($F(1,15)=24.87$, $p=.0002$), with response times being faster for the target present condition, due presumable to the earlier termination of search on target-present trials.

A verbal-memory task difficulty by target state by tracking difficulty interaction was observed ($F(2,30)=12.07$, $p=.0001$). Simple effect tests showed that the two way interaction, verbal-memory task difficulty by target state, was only significant in the easy tracking condition ($F(1,15)=23.10$, $p=.0002$). Post-hoc Tukey tests revealed that responses were significantly longer for the target-absent (i.e. probe letter was not in memory set) condition in the difficult (5 letter) condition ($p<.05$) but not different in the easy (2 letter) condition. This reflects the greater number of mental comparisons of letters in the five letter memory set.

B) Verbal-Memory Task Latency: Target-Absent Trials. A 2 (display location) X 2 (verbal-memory task difficulty) X 3 (tracking difficulty) X 2 (pedestrian state) repeated measures ANOVA examined the effects of pedestrian state on verbal-memory task latency. There was a small, but not statistically significant effect of display location (F $(1,15)=1.67$, $p=.21$) with responses to the HUD being slightly faster than responses to the HDD. There was a significant main effect for verbal-memory task difficulty, $F(1,15)=62.77$, $p=.0000$, with response times being significantly longer for the difficult condition (5 letter memory set) than the easy condition (two letter memory set). Also, a main effect for pedestrian state was computed, $F(1,15)=37.16$, $p=.0000$, with verbal-memory latencies slower when the pedestrian was present. This shows that participants followed instructions and prioritized braking for pedestrians above answering the verbal-memory task. No interactions were observed.

Pedestrian Braking Response Times (BRTs)

In each set of trials, half of the pedestrians appeared in the roadway 500 ms after the onset of the verbal-memory task, and half appeared randomly, when the verbal-memory task was not present; the latter served as a control measure. Overall, BRTs in the control condition (M = 959.83) were significantly faster ($F(1,15) = 52.43$, $p=.0000$) than when a braking response was required simultaneously with the verbal-memory task (M = 1104.81).

To assess attention switching, pedestrians appeared in the roadway 500 ms after the onset of the verbal-memory task in quasi-randomly selected target-absent trials (see Table 11). The BRTs were analyzed with a 2 (display location) X 2 (verbal-memory task difficulty) X 3 (tracking difficulty) repeated measures ANOVA. A main effect for display location was observed. BRTs were significantly faster in the HUD condition than the HDD condition $F(1,15)=10.12$, $p=.0062$, however, both were slower than the control condition (no verbal-memory task), $p<.05$, (see Figure 14). Apparently, participants took less time to return their attention to the tracking task after responding to the verbal-memory task in the HUD than the HDD, presumably due to the time required to move the eyes from the HDD to the roadway.

A main effect for tracking difficulty was found ($F(2,30)=8.78$, $p=.0010$). This finding cannot be interpreted unambiguously due to the presence of interactions, including a display location by tracking difficulty interaction, $F(2,30)= 5.23$, $p=.0113$, which is illustrated in Figure 15. Simple effect tests revealed that BRTs did not differ significantly as a function of tracking difficulty within the HUD condition. This is because HUDs facilitated the monitoring of the roadway while driving and responding to the visual tasks. BRTs did increase as tracking difficulty increased with the HDD condition $F(2,30)=9.06$, $p=.0014$. The HDD may have hindered critical event detection by precluding simultaneous

Table 11.

Means and Standard Deviations for Braking Response Times with the Verbal-Memory Task

Factor	Level	Mean (ms)	SD
Display Location	HUD	1052.57	220.74
	HDD	1157.05	305.43
Verbal-Memory Task Difficulty	Easy (2 letters)	1099.88	243.98
	Difficult (5 letters)	1109.75	296.57
Tracking Difficulty	Easy	1045.03	230.05
	Medium	1106.44	261.69
	Difficult	1162.97	306.58

Figure 14. Braking Response Time as a Function of Verbal-Memory Display Location

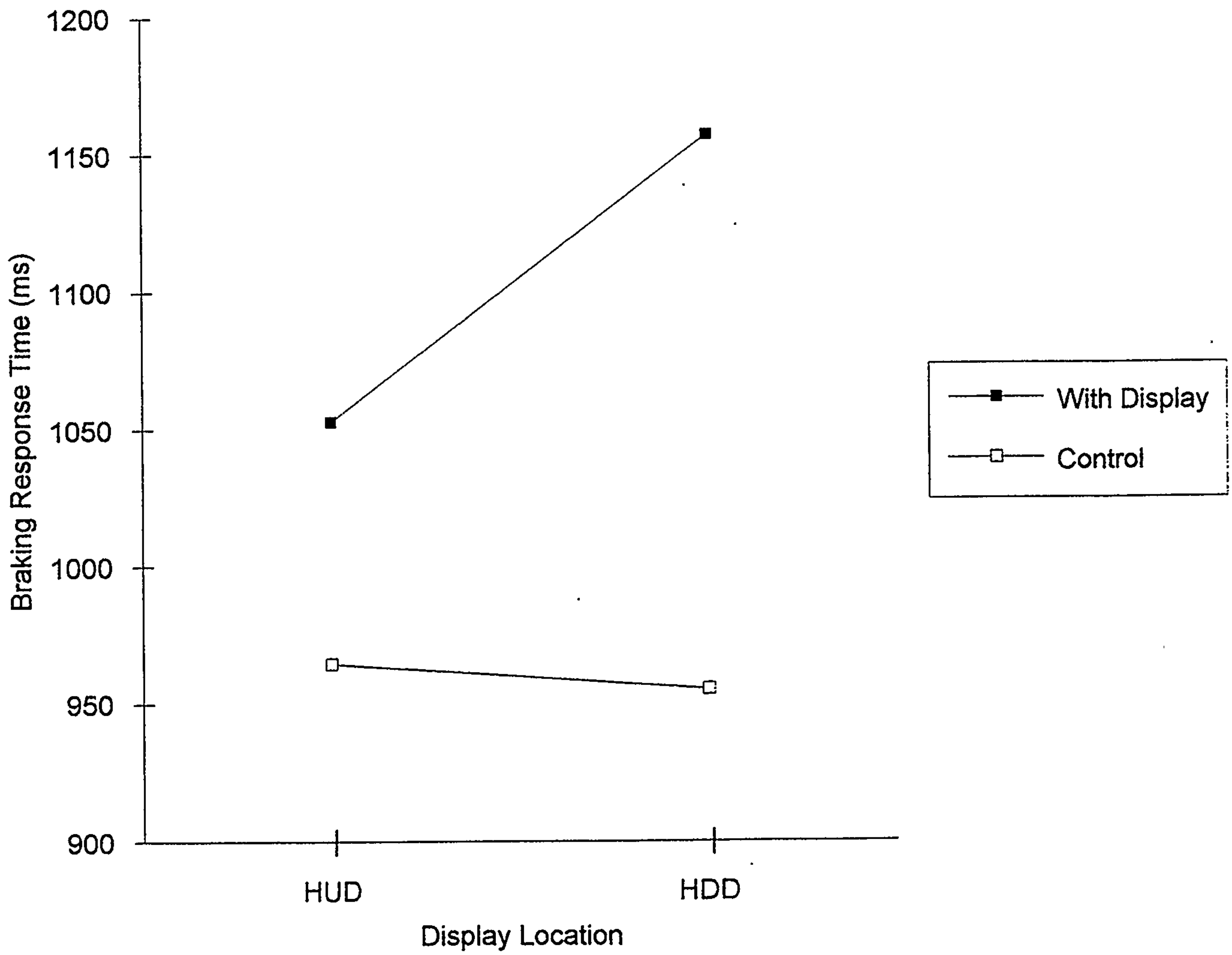
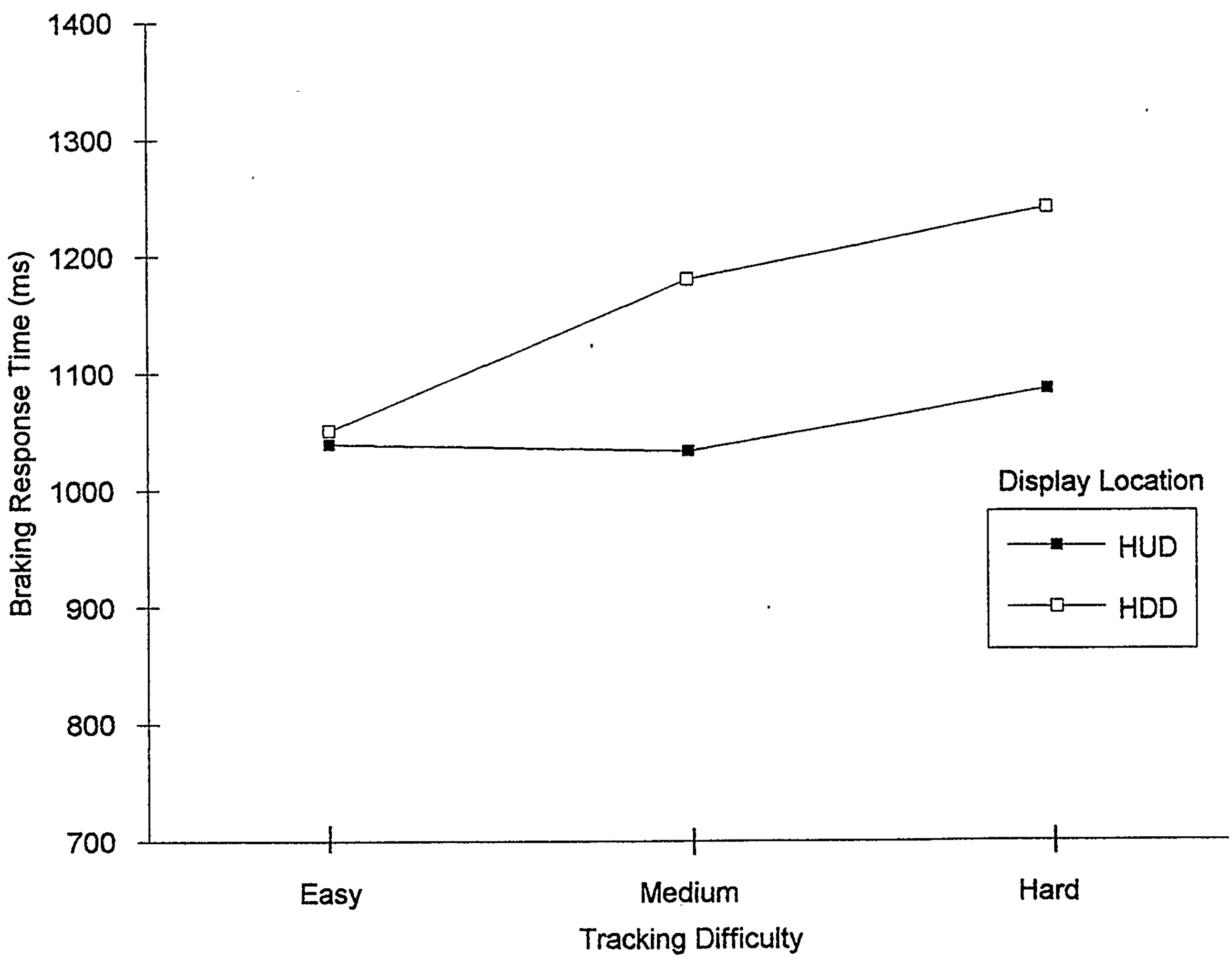


Figure 15. Braking Response Time as a Function of Display Location and Tracking Difficulty



monitoring of the display information and the simulated roadway.

Finally, a verbal-memory task difficulty by tracking difficulty interaction was observed, $F(2,30)=10.36$, $p=.0004$. Simple effect tests indicated that BRTs increased as tracking difficulty increased in the difficult (five letter) verbal-memory task condition, $F(2,30)=11.42$, $p=.0002$, but not the easy (two letter) condition, $F(2,30)=2.35$, $p=.1123$ (see Figure 16). Sharing of attentional resources between tracking and the verbal-memory display had a cost or added to the time necessary for a participant to brake.

Attentional Capture

Two blocks of trials at the end of each verbal-memory set were used to assess attentional capture. During these display-irrelevant trials verbal-memory tasks were presented which participants were instructed to ignore. Tracking and critical event BRTs were assessed.

A 2 (Display Location) X 2 (Pedestrian State) X 3 (Tracking Difficulty) repeated measures ANOVA was conducted on the tracking performance (RMS error) data from the display-irrelevant trials. Tracking did not differ significantly as a function of the location of the verbal-memory task ($F(1,15)=0.25$, $p=.6273$). Although the HUD was closer to the tracking task and thus more salient than the HDD, presenting irrelevant information in the HUD did not affect tracking performance.

For each set (HUD and HDD) of display-irrelevant trials, six pedestrians were presented 500 ms after the onset of the irrelevant verbal-memory task, and six were presented when the verbal-memory task was not displayed. The latter constituted the control measure. These HUD and HDD control BRTs (i.e. no display present) were compared (see Table 12) as a manipulation check and, as expected, no significant differences were detected ($F(1,15)=.43$, $p=.5208$). To

Figure 16. Braking ResponseTime as a Function of Verbal-Memory Task Difficulty and Tracking Difficulty

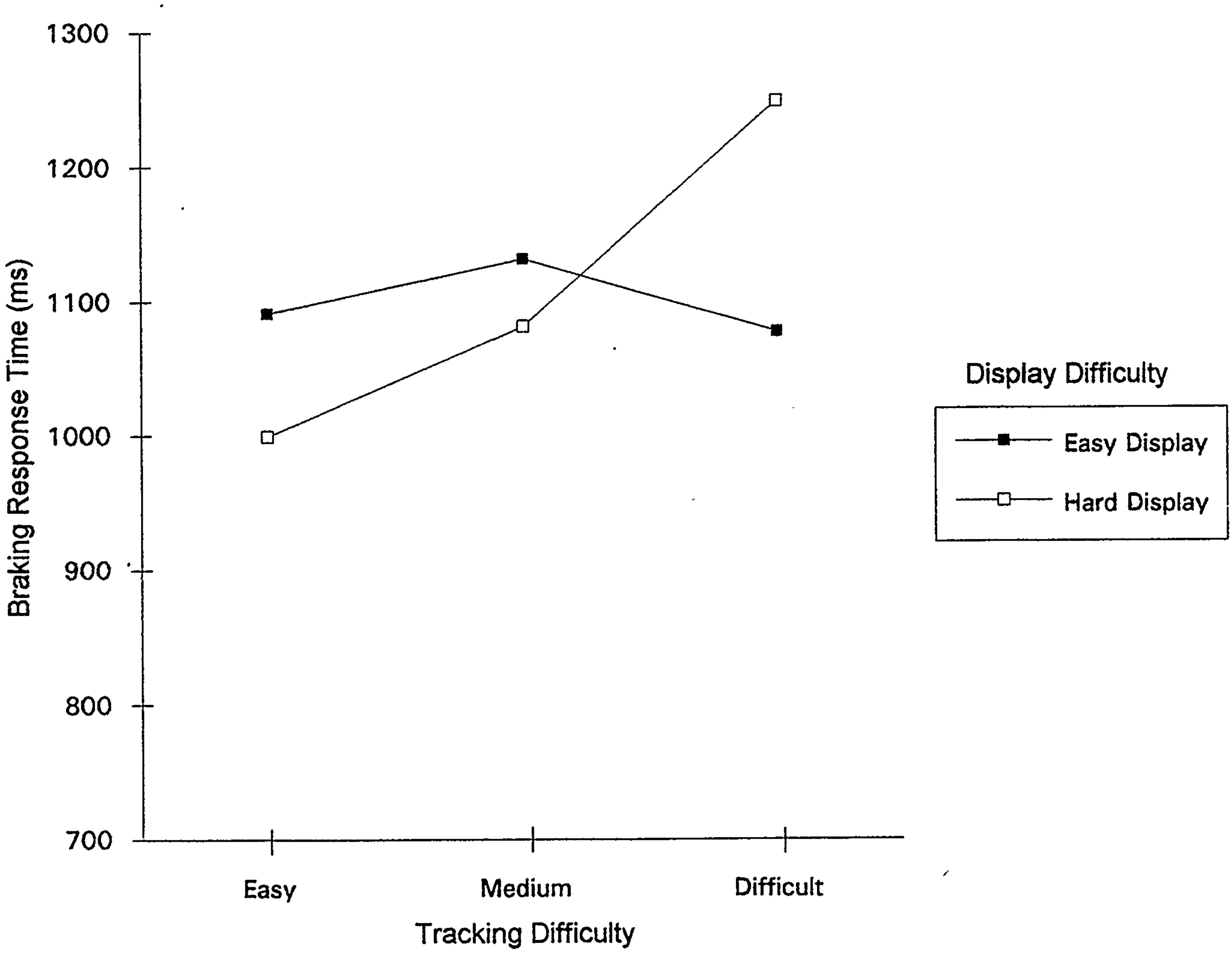


Table 12.

Means and Standard Deviations for Obstacle Braking Response Time for the Verbal-Memory Display-Irrelevant Trials.

Display Location	Mean (SD) Braking Response Time (ms)		Mean Difference
	No Display (Control)	Irrelevant Display	Control-Display
HUD	951.62 (272.10)	902.56 (165.12)	39.06
HDD	953.77 (166.55)	922.22 (231.75)	31.55
HDD - HUD	2.15	19.66	

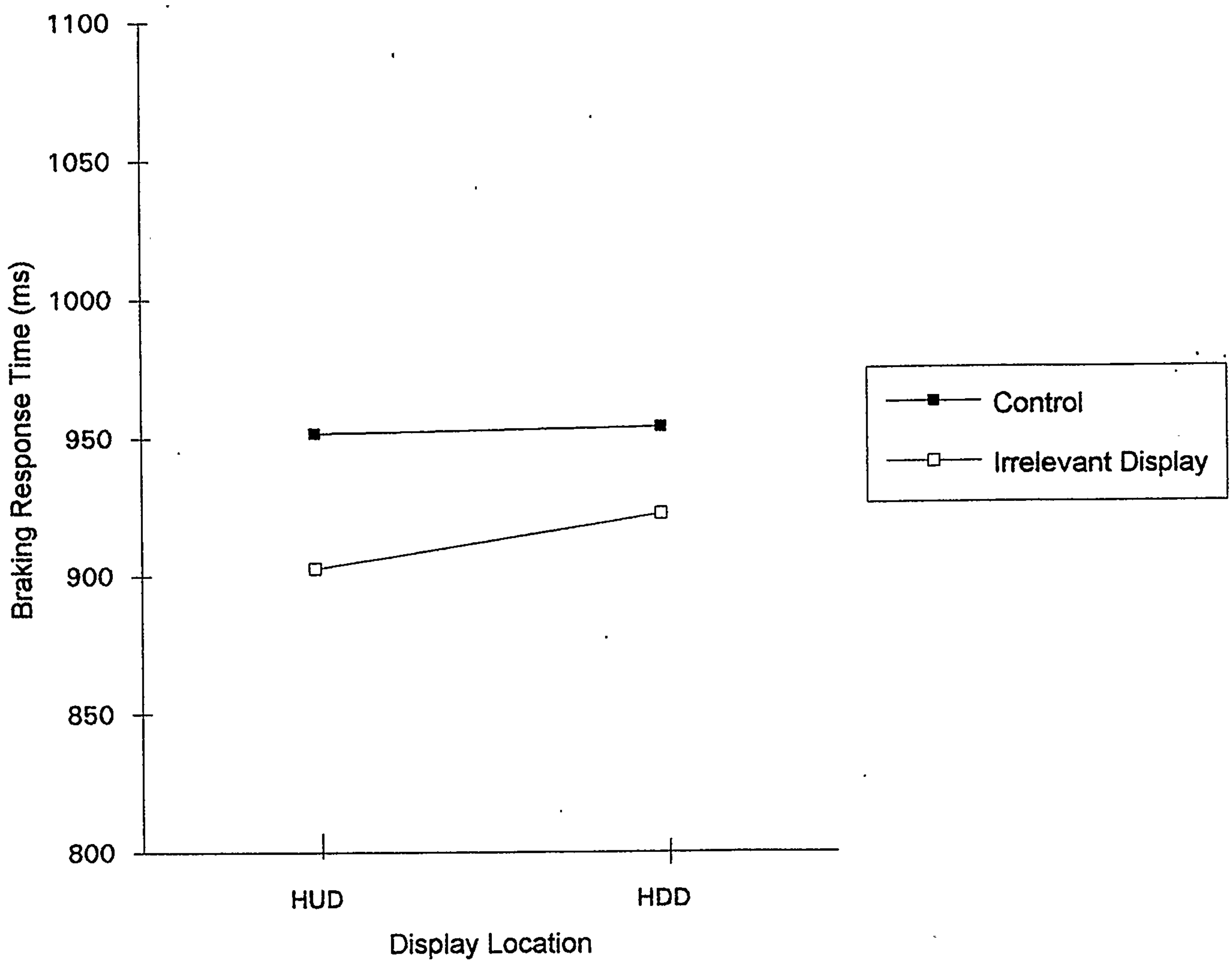
Note: There were no significant differences between any of the means.

determine if a participant's attention was captured by the display, BRTs in both the HUD-irrelevant and HDD-irrelevant conditions were compared to their respective control measures (no display trials) (see Figure 17). In the HUD condition, BRTs did not differ significantly between control and display-irrelevant trials (F (1,15)=1.97, p=.1809), indicating that the irrelevant HUD display did not affect braking performance. Similarly, BRTs in the control and HDD-irrelevant condition were not significantly different (F=(1,15) = .91, p=.3553). Thus, results suggest that participants were not drawn to the irrelevant display (HUD or HDD) at the expense of braking BRTs to critical events. To test the hypothesis that HUDs would be more salient and thus more likely to capture attention than HDDs, the effect of display location in the display-irrelevant trials was analyzed. There was no difference between HUD and HDD BRTs (F(1,15)=.43, p=.5208), which suggested that participants' BRTs were not affected by the location of the irrelevant display.

Summary

The results of the verbal-memory task analyses indicated that tracking performance was not affected by display location. Verbal-memory latencies were slightly speeded by the use of the HUD in the pedestrian-absent condition, and there was a small, but not statistically significant HUD advantage in the target-absent trials. Critical event detection was facilitated by the HUD, and further, there was a significant slowing of responses to critical events while using the HDD as tracking difficulty increased. There was no evidence to suggest that tracking performance and critical event BRTs were affected by the presence of the irrelevant verbal-memory task displayed in the HUD or HDD.

Figure 17. Braking Response Time with the Irrelevant Verbal-Memory Task



Sample Characteristics

Individual Differences

The results reported thus far are based on data averaged across all participants. The performance of each participant is represented in Table 13 which depicts the difference scores for each performance measure averaged across all factors, calculated by subtracting HDD performance from HUD performance. Negative scores (those in parentheses) indicate that a subject performed better with the HDD than the HUD. As shown, the HUD advantage, while pervasive was certainly not universal at an individual level. Thus, some drivers are able to take advantage of HUD information, while others may not.

Vision and Performance

To evaluate the possible role of spatial vision abilities on task performance, static acuity, average contrast sensitivity, peak contrast sensitivity, and spatial frequency at peak contrast sensitivity, were correlated with three performance measures used in the visual search and verbal-memory tasks: tracking error, braking reaction times, and display response latencies. For all three performance measures, higher values are associated with poorer performance (see Table 14). Tracking performance with the visual search task was negatively correlated with the average contrast sensitivity measure, and positively correlated with acuity despite the extremely restricted range of the acuity scores.

Driving Experience and Performance

To assess possible relationships between "real-world" driving experience and task performance, correlations between the two self-report measures of driving experience, years driving and distance (km) driven per week, and the

Table 13.

Individual Differences

Partic-pant #	Visual Search Task: Tracking Error (RMS)	Visual Search Task: Braking Times (ms)	Visual Search Task: Latency (ms)	Verbal-Memory Task: Tracking Error (RMS)	Verbal-Memory Task: Braking Times (ms)	Verbal-Memory Task: Latency (ms)
1	(0.02)	124.50	525.01	2.16	151.33	425.30
2	0.84	83.33	26.51	0.97	(784.00)	216.54
3	(0.87)	64.08	124.02	(0.17)	(28.92)	(106.18)
4	3.76	116.42	19.98	2. 18	123.17	208.68
5	(3.25)	97.08	36.33	(2.12)	141.50	362.97
6	(1.44)	45.75	347.00	0.06	526.00	(3.42)
7	(1.13)	(47.25)	121.22	0.45	(121.08)	178.60
8	3.97	61.92	18.06	(1.10)	531.17	36.29
9	(0.21)	(115.25)	(35.69)	(0.19)	798.25	(132.36)
10	5.68	54.41	669.71	3.58	79.50	124.02
11	0.23	26.91	355.72	(0.55)	5.92	85.87
12	2.27	342.58	558.09	(0.64)	133.08	434.30
13	(1.17)	(109.33)	442.95	(1.38)	(61.83)	183.82
14	2.95	33.67	200.39	(0.08)	48.25	(41.25)
15	(0.33)	142.33	139.27	(0.17)	68.00	3.96
16	1.82	3.17	300.07	4.05	24.83	(163.44)

Note: Scores represent the difference in performance between HUD and HDD presentations of the visual search and verbal memory tasks.

Table 14.
Correlations Between Visual Health Measures, Tracking Performance, Obstacle Braking Time, and Latency for the Visual Search and Verbal-Memory Tasks.

Vision Measure	Visual Search Task			Verbal-Memory Task		
	Tracking	Braking	Latency	Tracking	Braking	Latency
Acuity	.5376*	.2389	-.0757	.1890	.2910	.3740
Avg. CS	-.5260*	-.0444	.3361	-.4999	-.1675	.0878
Peak CS	-.4353	.1322	.3773	-.4926	-.0219	.1245
Peak SF	-.0072	-.2275	-.0166	-.1649	-.2746	-.0439

Note: N=16, 2-tailed Sig: * .05

three performance measures for both the visual search task and the verbal-memory task are reported. As can be seen in Table 15, years of driving experience was positively correlated with visual search latencies, and braking reaction times in both the visual search and verbal-memory sessions, suggesting that as years of driving experience increase, visual search latencies and braking reaction times also increase. Further examination of the sample's driving characteristics revealed that a number of the students reported having a driver's license for several years, however, do not drive on a regular basis at the present time. Thus, distance driven may be a more informative measure of driving experience.

Video Game Experience and Performance

Subjects were asked to report, on a scale from 1(not at all) to 6 (very frequently), the amount of time spent playing computer games, and the percentage of time that computer games involved the use of car, motorcycle, or airplane simulations. No significant correlations between this measure and task performance were seen (Table 16).

Self-Report Information and Performance

In addition, participants reported on a scale from 1 (none) to 4 (a lot), how much difficulty they had ignoring dirt and spots on their windshield, and how much difficulty they had concentrating when a passenger was talking in the car. As seen in Table 17, there was no apparent relationship between their reports and task performance.

Table 15.

Correlations Between Driving Experience, Tracking Performance, Pedestrian Braking Time, and Response Latency for Visual Search and Verbal-Memory Tasks.

Driving	Visual Search Task			Verbal-Memory Task		
	Tracking	Braking	Latency	Tracking	Braking	Latency
Years	.1058	.6073*	.5353*	-.0850	.5188*	.4602
Km.	-.1787	-.2027	-.1087	.2078	.0364	-.2832

Note: N=16, 2-tailed Sig: *-0.05

Table 16.

Correlations Between Video Game Experience, Tracking Performance, Pedestrian Braking Time, and Response Latency for Visual Search and Verbal-Memory Tasks.

Video Games	Visual Search Task			Verbal-Memory Task		
	Tracking	Braking	Latency	Tracking	Braking	Latency
A	-.0668	.1425	.1493	-.0734	.3930	-.0228
B	-.4175	-.3374	-.1034	-.3552	.3288	-.3412

Note: N=16, 2-tailed Sig: *-0.05
No correlations were significant

Note: Questions are as follows:

A) How often do you play video games?

B) How often do these games involve vehicle simulations?

Table 17.

Correlations Between Self-Report Measures, Tracking Performance, Pedestrian Braking Time, and Response Latency for Visual Search and Verbal-Memory Tasks.

Self-Report	Visual Search Task			Verbal-Memory Task		
	Tracking	Braking	Latency	Tracking	Braking	Latency
A	.2521	-.0966	.2746	.2207	-.2934	.3730
B	-.1500	.1166	.1733	-.1249	-.0413	.0080

Note: N=16, 2-tailed Sig: * 0.05
No correlations were significant

Note: Questions are as follows:

A) How much difficulty do you have ignoring dirt or chips in your windshield?

B) How much difficulty do you have driving while listening to a passenger?

Discussion

The findings of the present study clarify some of the attentional issues associated with HUD use and generate many more issues for further research. Specifically, the present study contributes to the literature by examining the effect of presenting spatial and verbal tasks in a HUD on driving performance. Also, the effect that HUDs have on attention switching and attentional capture in the driving domain were addressed in the present study. Theoretical and design issues are discussed.

Driving Performance

The hypothesis that overall tracking performance would be better in the HUD condition, except where high task load conditions may overload the driver, was supported by the visual search task, but not the verbal-memory task. A HUD advantage for tracking performance was revealed with the visual search task, in high-task-load conditions (difficult display and difficult tracking) when no braking response was required. In the HDD condition, with the same task demands, participants had to take their eyes off the tracking task and the sharing of attention between the display and the tracking task was not possible. However, when a pedestrian was presented along with the same high-task-load condition, tracking performance was worse with the HUD than the HDD. In this context, the attention sharing advantage of HUDs was negated because the task demands exceeded the participant's attentional capacity. Anecdotally, several participants mentioned that when the pedestrian appeared during the harder tracking and display task conditions, they could no longer do both tasks. Presumably the extent to which the HUD might overload attentional capacity is a complex function of driver experience, display characteristics, and roadway environmental variables. It must also be remembered that even with the practice provided, the participants were still relatively inexperienced with the simulated tasks studied. An examination of the sustained effects of HUDs on driving performance over longer periods of time is mandated.

Tracking performance was not differentially affected by display location in the verbal-memory task condition. This may have occurred because the divided attention advantage of the HUD was offset by the cost associated with overloading the attentional capabilities. This explanation is only speculative however, as these costs and advantages could not be quantified in the present study. Alternatively, the finding that the visual search task interfered with driving performance, but the verbal-memory task did not, can be explained by the multiple-resource theory (see Wickens 1980, 1984). The multiple resource theory suggests tasks will interfere with each other if they share the same resource pool (i.e., spatial or verbal processing resources). Wickens suggested that if two tasks employ different processing codes they will be time shared more efficiently than if two tasks share a common code. Because the tracking task in the present study is assumed to use spatial processing codes, it is reasonable to assume that the spatial (visual search) task would interfere with the tracking task more than the verbal-memory task because the same processing codes are needed. Under normal driving circumstances, HUDs may not hinder the division of attention so long as tasks require separate resources and that the pool of attentional resources is not used up by a single task. Under conditions of high environmental demands, such as rush hour traffic, driving at night, or in inclement weather, the addition of the HUD may hinder the division of attention between the traffic environment and the HUD.

The inconsistent benefit of HUDs is at odds with the results of Kaptein (1994) who showed that HUDs improved tracking performance in all levels of task load. However, Kaptein did not vary the task load of the analog speedometer display task, nor did he include a critical event detection task. As a result, the level of attentional task demands may have been significantly less than in the present study. That the current results found a HUD disadvantage only when the pedestrian appeared during the difficult visual search task, is consistent with this suggestion. Therefore, under high individual task demands of a HUD display in conjunction with adverse traffic environmental scenarios, HUDs may become an attentional liability.

HUD/HDD Task Latency

Shorter latencies for both the visual search task and the verbal-memory task when presented in the HUD provide support for the hypothesis that HUDs reduce the visual scan time necessary to extract information from a display. The HUD advantage was 262 ms for the visual search task and 125 ms for the verbal-memory task. Similarly, Kiefer (1991) found HUD advantages for a digital speedometer reading task of 100 to 150 ms in closed-track tests. From these consistent results, less time is required to acquire information from the HUD than the HDD. Presumably, the time savings are due to the spatial contiguity of the HUD and the driving task.

The HUD advantage in display reading times was greater for the visual search task (262 ms) than for the verbal-memory task (125 ms). Previous studies (Noy, 1990) have, perhaps inappropriately, attempted to equate the difficulty level of the two. However, the two tasks represent different information processes. The visual search task required visual attention such as would be required to visually detect and compare symbols. The verbal-memory task required short-term memory and working memory resources, as would be required by navigation and route-guidance tasks. Certainly, in the former, drivers needed to maintain eye contact with the display to perform the task successfully. In the verbal-memory task, however, mental comparisons were required that utilized working memory, but that did not necessarily require continual visual contact with the display.

Critical Event Detection

The hypothesis that the detection and response to critical events in the traffic environment would be faster with the HUD than the HDD was supported. Participants responded faster to the appearance of the pedestrian in the roadway with the HUD than the HDD in both the visual search (109 ms) and the verbal-memory (104 ms) tasks. The results represent a greater visual scan cost for the HDD that is roughly equivalent to a fast eye-movement (Card, Moran and Newell, 1986). Also, the HUD may have allowed for covert attention switching as eye movements were not required to switch attention from the display to the road. In real-world terms, a time savings of 104 to 109 ms translates into stopping approximately 3 meters sooner at 100 kph. Therefore, based on the present findings in a simulated task environment, the practical significance of HUDs in critical event detection would be modest. Nonetheless, the present study replicates Sojourner and Antin's (1990) findings of an advantage for HUDs in responding to critical events on the roadway, but extends their work to more realistic tracking and visual display demands. The HUD advantage in their study (440 ms) was much larger than the current results. However, their task did not require participants to perform a tracking or driving task, instead, their participants passively viewed a video tape from a driver's perspective. The lack of the lane maintenance task lowered attention demands.

The present findings do not support Weintraub and Ensing's (1992) prediction that HUDs would slow attention switching. This was predicted because HUDs reduce or eliminate cues that normally indicate that a switch of attention is in progress. These cues include the physical process of looking up, changing optical focus, and changing eye convergence. In the present experiment, changing optical focus was not part of task constraints. As a result attentional switching may not have been adversely affected because participants responded to the critical event in the roadway faster with the HUD than the HDD.

The results are also contrary to the findings of Wickens, Martin-Emerson, and Larish (1993) who found that the HUD conferred no advantage in switching attention from the display to the environment. The unexpected event in this study differed from Wickens, Martin-Emerson, and Larish; one was a pedestrian where the other was a runway light. In each situation, it is likely that urgency differed. The runway light, may not have created the same conditioned sense of urgency as the appearance of the pedestrian in the roadway.

Attentional Capture

It was expected that participants' braking reaction times would be slowed by the presence of the irrelevant HUD display if their response was stimulus-driven. Conversely, if participants used a goal-driven approach such that they allocated their attention to the goal of driving, obstacle braking times would not be affected by the presence of the irrelevant display. Braking response times to the pedestrian during display irrelevant trials (both visual search and verbal-memory) did not differ significantly whether the display was on or off. That participants did not appear distracted by the sudden onsets and offsets of the HUD is compatible with the goal-driven hypothesis of attention allocation and the supervisory/control context of visual sampling. These theories suggest that drivers can probabalistically allocate their attention to information-rich sources. Therefore, drivers may be able to attend to the driving environment and ignore the HUD despite sudden onsets of the display that are generally known to capture attention (Yantis and Jonides, 1984). In this study, goal-driven allocation of attention seemed to over-ride stimulus-driven allocation of attention as Bacon and Egeth (1994) suggested might be possible.

In Long and Wickens' (1994) aviation study, pilots were required to monitor their air speed and their aircraft's position with respect to the runway on several landing approaches. The air speed information was only presented in the HUD, and the runway position information was obtainable from both the outside world and the HUD. It was found that pilots allocated their attention to the HUD and not the runway, and thus failed to notice an unexpected aircraft blocking the runway. It can be argued that the pilots monitored the HUD and not the runway because it was a better source of information by which to guide the plane. As a result, pilots may have learned to sample the HUD information more frequently and for longer periods of time as a substitute for environmental information. In the driving task of the present study, the display information was clearly secondary to the tracking task. Therefore, drivers in the present study effectively directed their attention to the simulated road environment which provided information toward the goal of safe driving. The sudden onsets of the HUD were effectively ignored because the display provided only secondary status information, and not warnings critical to safety or environmental information (such as Vision Enhancement Systems).

The approach used to assess attentional capture, though very different from the approach used in past aviation studies (Fischer, Haines, and Price, 1980; Long and Wickens, 1994; Wickens, Martin-Emerson, and Larish, 1993), was thought to better reflect current real-world automobile HUDs. While the element of surprise in the present study was not equal to these in past aviation studies, the single samples from the runway excursions are in some ways equally problematic. Future studies are needed to systematically examine the effect of unexpected intrusions in higher fidelity simulations and field studies.

It is clear that given an instructional set, participants were not cognitively drawn to the display, at least to the extent that their performance suffered. However, perhaps a more critical question that requires further research is the extent to which driving performance would suffer in the absence of a goal-driven instructional protocol. That is, over habitual HUD use, onsets may condition drivers to glance at the HUD as part of the scanning of traffic and display information sources. When the HUD contains information of little value to the operation of the vehicle, it would be expected that the sampling of the HUD would be less then when HUD information is particularly salient.

Individual Differences

The individual difference data suggest that some drivers might be able to take advantage of a HUD, whereas others might be disadvantaged by them. At least half of the participants performed better in the HDD condition in both the visual search and verbal-memory tasks, although the differences were small and not statistically significant. Large HDD advantages were shown by some participants in the critical event detection task, however, these effects were off-set by a larger number of participants who showed a HUD advantage. Future research needs to determine the characteristics of HUDs that benefit some drivers and disadvantage others. Participant age, gender, visual characteristics, driving experience, computer experience, previous HUD use, and self-report driving problems, did not provide any insight into the basis of these individual differences. One driver attribute that might address these individual differences is perceptual style or field dependence, the ability to perceive relevant targets embedded within distracters (e.g. Goodenough, 1976). Field-dependent individuals are less able to isolate an item from its background, a limitation with obvious implications for HUD design and utilization. This should be examined in future research.

Static visual acuity and tracking error in the visual search sessions were positively correlated, suggesting that as acuity increased so did tracking error. However, all but two participants had 20/20 vision or better. The performance measures of the remaining two participants (who had 20/30 vision) do not explain this potentially spurious finding. Average contrast sensitivity was negatively correlated with tracking error in the visual search task sessions. This means that as contrast sensitivity abilities increased, tracking error decreased. This is consistent with Evans and Ginsburg (1985) who reported that, compared to static acuity, contrast sensitivity was a better predictor of real-world visual task performance; reading stationary traffic signs while moving.

As the number of years of driving experience reported by the participants increased so did their braking response times in both the visual search and verbal-memory sessions. Visual search latency was also positively correlated with the number of years of driving experience. Although this correlation likely reflects the inadequacy of the measure to properly tap the driving experience of the sample; the participant with the fewest years of driving experience logged the highest distance per week, whereas some participants reporting several years of driving experience, did not drive at all, at the time of the study. It is possible that braking times were slowed because the simulated testing environment was sufficiently different from their real driving environment. Future improvements to the fidelity of the simulated traffic environment should attempt to minimize this possibility.

Self-reported video game experience was not correlated with any of the performance measures. Thus, the results are likely not due to the participants' differential experience with simulated vehicle tasks and video games.

Finally, although no correlations were found between performance measures and self-reports of difficulties ignoring dirt or chips in the windshield and driving while listening to a passenger, these may prove to be important variables with older drivers.

Ecological Validity

It is necessary to discuss the ecological validity of the present study to determine the degree to which the findings generalize to the real driving environments. Schiff and Arnone (1995, p. 27) argue that ecological validity does not necessarily imply that replication of everything in a laboratory or testing situation should be just as it is in the real world. Such an approach would be so expensive and time consuming that it would be virtually impossible. Instead, they argue that to obtain ecological validity, researchers must select the processes and situations that typify driving and utilize stimuli similar to those in the laboratory (also, see Forbes, 1972, p.37; Neisser, 1976). Similarly, Riccio (1995, p. 122) stated that "...simulation should be based on an epistemology that is commensurate with the tasks performed in [flight] simulators and with those aspects of the human and environment that are meaningfully related to these tasks". Thus, the degree that the HUD and driving simulation approximated real driving is discussed.

The compensatory tracking task was designed to approximate the lane maintenance component of the task of driving. In many ways it resembled driving in the real world, but perhaps more importantly it approximated the mental workload of driving. The lowest difficulty level was carefully specified that it did not exhaustively tap the driver's workload, allowing the driver to attend to other tasks. The most difficult level was designed to increase task workload so that little attentional resources remained for other tasks to be performed.

The critical event, a pedestrian appearing on the roadway, served the purpose of encouraging drivers to continuously scan the roadway as they would in a real driving situation. BRTs in the present study are comparable to those found by Olson and Sivak (1986) in real world trials. Olson and Sivak found that for completely unalerted braking conditions, in which participants were not forewarned of an obstruction on the roadway, the BRT ranged from about .8 to 1.8 seconds. This is comparable to the first braking response required of participants in the baseline trials of the present study, for which the mean BRT was 1.12 seconds. Furthermore, Olson and Sivak, found that when drivers were alerted that a braking response would be required, but were not told when and where to expect the obstacle, BRTs ranged from 0.5 to 1.4 seconds, and were on average approximately 0.2 seconds slower than the unalerted BRT. The pedestrians presented in the experimental trials of this study are comparable to the alerted condition in Olson and Sivak's study in that participants were warned that a pedestrian may appear, but were not told when or where. The mean 'alerted' BRT in the present study was 1.019 seconds, revealing a difference of about 0.1 second between the unalerted BRT (first braking response) and alerted BRTs (remaining braking responses). Thus, the BRTs obtained in the present simulated task are comparable to the distributions obtained Olson and Sivak.

The vertical separation of the HUD and HDD approximated a real automobile. The HUD was located approximately 5 degrees below the tracking task and was based on a General Motors automobile HUD currently in production (e.g., Kiefer, 1991). Similarly, the HDD was situated 15 degrees below the tracking task and approximated the location of traditional dashboards.

Although the visual search and verbal-memory tasks did not typify current automobile HUDs, the visual search task was designed so that it would resemble tasks where searching for and comparing different symbols are important. Analog speedometers or warnings such as fuel levels are real-world tasks that require visual search. The cognitive demands of the verbal-memory task are not unlike those involved in tasks such as using a digital speedometer or verbal route guidance systems. Though the results from the present study may generalize to secondary status automobile HUDs, they are probably less representative of critical warning, or environmental (Vision Enhancement Systems) displays.

Limitations of Present Study

The present study was conducted as a within-subject design which maximized statistical power. The possibility of fatigue, operator inexperience, and asymmetric transfer effects may have increased as a by product of the experimental design. In an effort to minimize fatigue effects, the experiment was separated into two 90-minute sessions held on separate days. Likewise, participants were encouraged to take regularly scheduled rest breaks and to relieve eye fatigue by changing their focal distance between blocks of trials. Secondly, to prevent operator inexperience from biasing the results, participants underwent comprehensive training sessions to ensure that they met criterion levels of performance before beginning the experimental trials. Lastly, asymmetric transfer (Poulton, 1982), or the possibility that the effects of participating in the HUD condition before the HDD condition would be different than the effects of participating in the HDD condition before the HUD, may be a source of bias in the results. Poulton suggested that asymmetric transfer is most problematic in an experiment where participants would normally use two or more different strategies in different conditions. It is not possible to determine whether different strategies were used by participants to extract information from the HUD and the HDD. Research that analyzes eye movements and subtle performance changes is needed to clarify these driver behaviours. Also, Poulton suggested that interleaving two conditions randomly in the same block of trials maximizes the transfer between two conditions. The current study presented all HUD blocks in one set and all HDD blocks in another set, in an effort to minimize asymmetric transfer. Although great care was taken to ensure that fatigue, operator inexperience, and asymmetric transfer effects did not bias the results, they must be acknowledged as potential problems in every within-subjects design experiment.

Areas for Future Research

Older Drivers. Despite the rapidly growing numbers of elderly drivers on the road, and the distinct possibility that the benefits and problems of HUDs could be very different for this group, little is known about the effectiveness of HUDs as a function of driver age. According to the Transportation Research Board (1988) about 12% of the American population is over the age of 65. This is the fastest growing demographic group in the country and by the year 2020, those over the age of 65 will constitute about 17% of the population. Elderly drivers compose the fastest growing segment of the driving population. In 1970 they represented 8% of drivers in the U.S., a figure which climbed to 13.4% by 1990 (U.S. Department of Transportation, 1976, 1991). Given these demographic changes, it is imperative that the sensory and cognitive declines experienced by older drivers be considered in the design of HUDs. Kline, Kline, Fozard, Kosnik, Schieber, and Sekuler (1992) examined the self-reported visual problems of older drivers. They found that as age increased, problems on the following five dimensions also increased: being surprised by unexpected vehicles, judging their vehicle speed, reading dim displays, seeing past glare and haze on the windshield, and quickly reading street signs.

On one hand, the reduction in visual accommodation and scanning requirements suggests that HUDs may be beneficial for the older driver in that they would be able to retrieve information from the display faster, and potentially detect obstacles or dangers on the roadway faster, thus allowing more time to respond. Also, the nature of the information presented in a HUD may prove to be beneficial for older drivers. For example, a collision avoidance system could potentially warn an older driver of unexpected vehicles in the periphery. A HUD speedometer would make speed monitoring easier, while traffic signs or route guidance information presented in the HUD would provide the information to the driver sooner, such that older drivers would have enough time to execute the desired response.

However, if designed improperly or without consideration of the limitations of divided and selective attention, HUDs may impair elderly driving. As was seen in this study, HUDs may overload the attentional capacity of young drivers in high-task-load conditions. This might well occur even more readily among their older counterparts as there is evidence older drivers have more difficulty on divided attention tasks (e.g., Parasuraman and Nestor, 1993; Somberg and Salthouse, 1982). A HUD could also exacerbate some of the problems that older drivers experience as a result of a more restricted useful field of view (UFOV) (Ball and Owsley, 1991). UFOV is the visual field from which information can be acquired during a brief glance (Sanders, 1970). One factor that may affect the size of the UFOV is the attentional demands of a central task.

Thus, as the cognitive demands of the HUD tasks increase, the UFOV may constrict, and objects in the periphery would be less likely to be detected.

Other research has indicated that the older adults have difficulty in discriminating relevant from irrelevant information as is the case of transiently relevant information such as HUDs. Rabitt (1965) found that in visual search tasks, older adults were slowed to a greater degree by the presence of irrelevant information than were young adults. Older adults became increasingly slowed as the number of distracters increased, thus revealing a display size effect. Subsequent studies have replicated the findings of a display size effect among the elderly (e.g., Plude and Dourrand-Roosevelt, 1989) and have also shown that they increase with target-distracter similarity (Scialfa and Esau, 1989).

Type of HUD information. Further research is also required to determine the impact of critical warning information and environmental information presented in automobile HUDs. In the present study, because only secondary status HUD tasks were utilized, drivers could effectively prioritize responses and focus attention on the task of driving. This may not be the case if HUDs present warning information (i.e. collision avoidance systems) such drivers learn that an onset or movement of the HUD might be associated with a danger (i.e. an impending collision). This would be particularly problematic if there is variability in the degree to which HUD information is critical. Then, every piece of information presented in the HUD has the potential to demand immediate attention of the driver to determine whether it is critical or not.

Also, further research is required to examine future HUDs that are intended to substitute environmental information. For example, vision enhancement systems (VES) are intended to be used in conditions of fog or snow, where environmental information, such as lane markings on the road, is not available to the driver. These systems are similar to aviation displays in that they are used as a primary source of information for operating the vehicle. Future research must consider that drivers may become used to relying on the display information and thus focus attention on the display instead of the environment. If this is the case, critical events in the environment that are not reported in the HUD may go undetected.

Theoretical Conclusions

The results have implications for researchers of automobile head-up displays. The present findings show that under normal conditions HUDs can facilitate divided attention under conditions of low and moderate tracking demand. However, in high-task-load conditions HUDs may overload the drivers' attentional capacity, thereby negatively affecting driving performance. Future examinations of HUD technology should include high-task demands, as it is in these conditions that accidents are most likely to occur. Second, the present study is consistent with earlier studies in demonstrating that drivers can retrieve information more quickly from the HUD than the HDD, apparently due to the spatial contiguity of the HUD and the outside environment. Third, this study suggests that attention switching is facilitated by the HUD, perhaps because it reduces the need to move the direction of gaze. Fourth, the results of the present study also imply that drivers, at least younger drivers, can effectively allocate their attention using a top-down or cognitive approach. This suggests, that when only non-critical status information is presented in the HUD, drivers may not be drawn to it to the exclusion of the traffic environment. This last finding highlights the importance of conducting further research to examine the individual and interactive effects of driver age and experience, driving environment, HUD experience, and HUD information and format on driving performance.

HUD Design Implications

Some critical HUD design issues about the information that may be presented in a HUD have been raised. Despite evidence that HUDs can be of benefit to drivers, their apparent ability to overload attentional capacity points to two critical design issues. First, HUD information should not exceed attentional resources in worse-case scenarios (i.e. an inexperienced driver in heavy traffic and inclement weather). Presentation of visual-spatial information appears more likely to overload the driver than the presentation of verbal-memory information because they use different processing codes (see Wickens, 1980, 1984). Second, user-controlled HUD onsets will allow the user to display the type, amount and even format of information when the traffic environment allows it.

Conclusions based on a comparison of driving and aviation studies suggest that presenting the most critical warning information in the HUD, or a combination of critical and status information, may be dangerous due to its alerting nature. Furthermore, results from aviation HUDs and the supervisory/control context of visual sampling, suggest that if drivers come to rely on the HUD for environmental information they may focus on it to the exclusion of the roadway. Further research is needed to optimize the allocation of task information to different display types, including HUDs.

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Appendix A
Driving Experience Questionnaire

This questionnaire should take you about 10 minutes to complete. Your participation in the study is known **only** to the researcher. All responses are strictly confidential. No names or other identifying data will ever be disclosed to others.

GENERAL INFORMATION

1. What is your education level?
   - Less than high school........................ 1.____
   - Some high school........................ 2.____
   - High school graduate........................ 3.____
   - Undergraduate degree (specify year)........................ 4.____
   - Masters Degree (specify year)........................ 5.____
   - Ph.D. (specify year)........................ 6.____

2. On average, how many hours a week do you spend playing computer games or video games?
   - Never........................ 1.____
   - Under 5 hours........................ 2.____
   - 6 hours to 10 hours........................ 3.____
   - 11 hours to 16 hours........................ 4.____
   - More than 16 hours........................ 5.____

3. If you play video games at all, what proportion of the time do they involve the use of a joy stick?
   - Never........................ 1.____
   - 20% or less........................ 2.____
   - 21-40% .... 3.____
   - 41 - 60% .... 4.____
   - 61 - 80% .... 5.____
   - 81 - 100% .... 6.____

4. If you play video games at all, what proportion of the time do they involve the use of a flight yoke or steering wheel (i.e. flight simulator, automobile racing, and motorcycle racing games)?
   - Never........................ 1.____
   - 20% or less........................ 2.____
   - 21-40% .... 3.____
   - 41 - 60% .... 4.____
   - 61 - 80% .... 5.____
   - 81 - 100% .... 6.____

5. Are you predominantly right or left handed? Right____ Left____

VISION INFORMATION

1. Do you wear glasses or contact lenses for driving? Yes ____ No ____
2. What optical correction are you wearing today, if any?
   - None .... 1.____
   - Distance (driving) .... 2.____
   - Near (reading) .... 3.____

3. Are you near sighted? Yes ____ No ____
4. Are you far sighted? Yes ____ No ____
5. Do you wear bi-focals? Yes ____ No ____

YOUR DRIVING EXPERIENCE

1. Do you have a valid driving license? Yes ___ No ___

2. Do you drive a motor vehicle (car, truck, motorcycle...) Yes ___ No ___

<u>Please complete this section only if you drive.</u>

3. How long have you been driving? ______ years

4. On average, how many *hours* do you drive a week? ______ hours

5. On average, how many *kilometers* a week do you drive? ________ km.

6. How often do you drive in rush hour traffic?
   - Very frequently .... 1.____
   - Frequently .... 2.____
   - Occasionally .... 3.____
   - Seldom .... 4.____
   - Never.......... 5.____

7. How often do you drive at night?
   - Very frequently .... 1.____
   - Frequently .... 2.____
   - Occasionally .... 3.____
   - Seldom .... 4.____
   - Never.......... 5.____

8. How often do you drive on/in each of the following conditions: (1-very frequently, 2-frequently, 3-occasionally, 4-seldom, 5-never)

Rural or sparsely populated area..____
Small town..____
Suburban...____
Urban..____
High-density urban...____

9. How much difficulty do you have ignoring dirt, haze or rain drops on your windshield?

None at all ____ A little ____ Quite a bit ____ A lot ___

10. Do you ever have difficulty concentrating on driving when someone else in the car is talking?

Never ___ Rarely ___ Occasionally ___ Frequently ___

11. Have you ever been surprised by a pedestrian suddenly crossing into the street?

Never ___ Rarely ___ Occasionally ___ Frequently ___

12. Have you ever driven in a car that had a "heads-up display", or that displayed the speedometer or other information on the windshield?

Yes ____ No ____

Appendix B
Sample HUDWare Script

```
[CONFIG]

set session_id 01                          ; indicates script number
set poll_interval 64                       ;64Hz (16 times / second)
set joy_event_capture JUSTNEW              ; polls just changed inputs
set object_event_capture ALLCAP            ; polls just changed inputs
set xc STICK_A                             ;Stick A used for X control
set yc STICK_A                             ;Stick A used for Y control
set signal_1_switch fire_A1                ;Button A1 used for 1st response set
signal_2_switch fire_A2                    ;Button A2 used for 2nd response
set signal_3_switch fire_b1                ;Foot pedal used for brake

set display_type HUD                       ;display location is HUD
set task_type SPATIAL                      ;task type is spatial
set aux_difficulty EASY                    ;Auxilliary difficulty is easy
set track_difficulty none                  ;Sets initial tracking as none
set obstacle_mode OmMAN                    ;Sets mode initially as manual

assign xlatproc PARSLOG2.EXE               ;assigns post-processor
assign rdf  01.LOG                         ; names the raw data file
assign pdf  01.ASC                         ; names the processed data file

[BODY]

;warm up - no aux task
00.00.01 adjust td easy

;trial 1
00.07.00 adjust td easy
00.14.00 nextprobe target 4096

;trial 2
00.21.00  adjust td hard
00.28.00  nextprobe notarget 4096
00.28.50  POPUP rz 2056

;trial 3
00.35.00 adjust td medium
00.42.00 nextprobe notarget 4096
;trial 4
00.49.00 adjust td medium
00.56.00 nextprobe target 4096

;trial 5
01.03.00 adjust td hard
01.10.00 nextprobe notarget 4096
```

```
;trial 6
01.17.00 adjust td easy
01.21.00 POPUP lz 2056
01.24.00 nextprobe target 4096

;trial 7
01.31.00 adjust td medium
01.38.00 nextprobe notarget 4096

;trial 8
01.45.00 adjust td easy
01.52.00 nextprobe notarget 4096

;trial 9
02.00.00 adjust td hard
02.07.00 nextprobe target 4096

;trial 10
02.14.00 adjust td medium
02.19.00 POPUP rz 2056
02.21.00 nextprobe target 4096

;trial 11
02.28.00 adjust td hard
02.35.00 nextprobe target 4096

;trial 12
02.42.00 adjust td easy
02.49.00 nextprobe notarget 4096

03.00.00 stop
[END]
```

Appendix C
Actual and Angular Dimensions of Visual Components

Visual Component		Actual Size (cm)	Visual Angle (degrees) Minimum Distance (52 cm)	Maximum Distance (75 cm)	Average Distance (64 cm)
Screen Size	Width	40	42.08	29.86	34.7
	Height	30	32.18	22.62	26.38
Driving Lane	Width	15	16.41	11.42	13.37
	Length	24	25.99	18.18	21.24
Car Icon	Width	2	2.20	1.53	1.79
	Length	3	2.96	2.29	2.69
Tracking Box	Width	2	2.20	1.53	1.79
	Length	3	2.93	2.29	2.69
Pedestrian	Width	1	1.10	.76	0.90
	Height	1.5	1.65	1.15	1.34
HUD/HDD	Width	6	6.61	4.58	5.37
	Height	3	3.31	2.29	2.69

Appendix D
Protocol of Instructions to Participants:
One Sample Order

General Instructions

Thank-you for volunteering for this study. I would like to begin by saying that your participation is entirely voluntary and that you are allowed to withdraw from this experiment at any time and for any reason. Are there any questions? Will you please sign the consent from?

Provide participant with consent form.

First, your visual acuity and contrast sensitivity will be assessed. This is just to get an idea of your general visual health Then, you will be asked to fill out a questionnaire to ascertain demographic and visual characteristics, your driving experience, and your computer/video game experience.

Test visual acuity
Test contrast sensitivity
Administer questionnaire

In this experiment, I am investigating the use of head-up displays in automobiles. Have you ever heard of, or driven with, a head-up display?

A head-up display presents information, such as the speedometer, on the windshield. Actually, it can present any information that is normally found on the dash board. I am going to ask you today to drive a simulated car in a simulated environment. Within this environment, you will be required to operate a vehicle just as you would if you were driving your own vehicle on the road. To do this, you must keep your vehicle in the center of a lane while responding to visual tasks presented either in a HUD or via a typical instrument panel.

Equipment Set-up

First, take a few minutes to adjust your seat position so that you are comfortable; just as you would if you were about to drive a real car. Once you have started, you will not be able to adjust the position of the chair or any of the other equipment.

Next, adjust the height of your chair so that your eyes are horizontal with this point (refer to the center point of the tracking task as marked on the screen). You can move the steering wheel so that is closer or farther away from you.

Would you like to make an adjustment. Also, we can adjust the angle of the steering wheel, as in tilt steering in a normal car, would you like to adjust the angle?

Now rest your right foot on the accelerator pedal below. We can move the pedal closer or farther away, and to the left or right if you wish. Remember, you will need to be able to move your foot from the accelerator to the brake as quickly as possible, so please make sure you are in a comfortable position to do so. Also we can adjust the height of the foot pedals if necessary.

Tracking-alone practice trials

Today you will be asked to complete a number of trials that approximate the real task of driving. Your task will be to keep the red car still and centered in the middle of the lane. A black box marked on the lane will help guide you. The car will be moving randomly up and down, and left and right in the lane. Your job is to compensate for these movements and keep the car still in the box.

To move the car: left: turn the steering wheel to the left.
right: turn the steering wheel to right.
forward in the lane: push the steering wheel forward
backward in the lane: pull the steering wheel toward you

When driving in the real world, you have to constantly watch out for pedestrians and other vehicles that may be on the roadway. If you see anything on the roadway, press the brake pedal as fast as you can. The acceleration of the car is programmed so you can rest your foot on the accelerator, but it will not affect the speed of the car. This is just a practice trial so you can get a feel for the car and the steering wheel.

Three 5 minute tracking alone trials; difficulty presented quasi-randomly

Display Tasks

In addition to keeping your car in the center of the lane and responding to cars and pedestrians on the roadway, you are also required to retrieve information from the instrument panel. I will be testing you in two conditions today. In the first, information will be shown about here on the screen (point to HUD location). This approximates the location of a real HUD. In the second, information will be presented about here (point to HDD location), and will approximate the location of a real instrument panel in a car. You will never receive both at the same time, and I will tell you before each trial which one you should expect.

Visual Search Display Task Alone

You will see a number of vertical lines in the display. Your task is to determine if one line is shorter than all of the rest. That is all lines will be identical in height, except sometimes one line will be shorter than the rest. If the short line is present, press the right button on the steering wheel. It is marked with a "Y" for 'Yes, the short line is present'. If you do not think a short line is present, press the left button, marked "N" for 'No the short line is not present'. Do you have any questions? If no, repeat: So remember, if there is a short line present, press the right button. If there is no short line present, press the left button.

The lines will appear on the screen for 5 seconds at which time they will automatically disappear whether you have responded or not. You can still respond even after the display has disappeared. It is most important that you are accurate so be sure of your answer, but, I am also recording your reaction time as well, so respond as accurately and as quickly as you can.

A number of these line tasks will be presented in a row. Keep responding until the screen goes blank. Do you have any questions? Are you ready to try this? These are just for practice. For now, you can ignore the car you do not need to steer for this trial.

On this trial, there will be two lines presented in the HUD. Remember, press the right button if one is shorter than the other. Press the left button if they are the same length.

2 blocks of 12 easy visual search task alone trials

This trial will be the same as before, except there will be more lines in the display. It will be presented in the HUD/HDD also.

2 blocks of 12 difficult visual search task alone trials

Dual task Practice Trials

Now we will combine all the tasks you have learnt. You will be required to keep the car still and centered in the target box. A pedestrian may appear anywhere on the roadway and at any time. Brake as quickly as you can to the pedestrian on the roadway, and return to the driving task. The car icon will not actually stop, but your brake press will be recorded. The brake pedal is very sensitive, so you just need to tap the brake quickly and then continue driving as normal. Just like in the real world, your first priority always is to drive. This involves controlling your car and braking if you see pedestrians on the road. You should always ensure that these tasks are under control before answering the line task. Remember, I am recording your accuracy and speed of the line task.

Confirm that participant understands that driving (controlling car and braking for pedestrian) comes first and responding to the line task is secondary. Are you ready to try these tasks together? They are just for practice.

This time, the display will have two lines.

2 blocks of 12 easy visual search trials and tracking

OK. Same thing again, this time, the display will include 12 lines. Still just for practice.

2 blocks of 12 difficult visual search trials and tracking

Session 1 (Day 1)

Now, we are about to embark on the experimental trials. They will be identical to the last two blocks of trials that you just completed.

I am going to ask you to remain at the task until the screen goes blank. When the screen goes blank, you may rest your eyes by changing the focus point. For example, you may want to look at the far wall for a few seconds. Please do not get up and leave the computer between blocks of trials.

Set One

You will complete six blocks of trials. At the conclusion of the sixth block, you will be permitted to take a five to ten minute rest period.
Are you ready? Remember, as in the real-world, driving and braking for pedestrians is your first priority.

Visual Search Trials in the HUD (orders 1-4 counterbalanced)

1 easy display task block
2 easy display task block
3 hard display task block
4 hard display task block

Visual Search Display-Irrelevant Trials

For the following blocks, the lines will be presented, as before. This time, just ignore the lines. You are not required to press the response button. Keep driving and braking for pedestrians as before.

5 display-irrelevant block
6 display-irrelevant block

OK, you may now take a rest period of approximately five minutes. You may get up and stretch if you wish.

5 to 10 minute rest break

Set Two

Please return to your seat at the apparatus and make sure that you are sitting in the same position. When you have returned to your comfortable position, I will re-measure your position to ensure that you are sitting the same distance away from the computer.

We will begin set two now. The trials will be exactly the same as before, except this time, they will be presented in the HDD (point to location on screen).

Visual Search Task Alone

Just so you get used to the new location, these trials will let you practice the line task, by itself. Remember, press the right button if one is shorter than the other. Press the left button if they are the same length.

1 block of 12 easy visual search task alone trials

This trial will be the same as before, except there will be more lines in the display. It will be presented in the HUD/HDD also.

1 block of 12 difficult visual search task alone trials

Dual task Practice Trials

Now we will try practice the line task along with the tracking task. Remember that driving (controlling car and braking for pedestrian) comes first and responding to the line task is secondary. Are you ready to try these tasks together? They are just for practice.

This time, the display will have two lines.

2 blocks of 12 easy visual search trials and tracking

OK. Same thing again, this time, the display will include 12 lines. Still just for practice.

2 blocks of 12 difficult visual search trials and tracking

We will begin the experimental trials for the second set now. Ready?

Visual Search Trials in HDD (orders 1-4 counterbalanced)

1 easy display task block
2 easy display task block
3 hard display task block
4 hard display task block

Visual Search Display-Irrelevant Trials

For the following blocks, the lines will be presented, as before. This time, just ignore the lines. You are not required to press the response button. Keep driving and braking for pedestrians as before.

5 display-irrelevant block
6 display-irrelevant block

Thank-you very much. That is all for today. Any questions? Can you still make our next session on (insert date)? It is very important that you attend that session if you can, as the second session has to be completed within three days of the first session.

Session 2 (Day 2)

General Instructions

Thank you for coming back to complete the test. The test today will be similar to last day, and again will require about 90 minutes of your time. The same holds true as it did last day, this is an entirely voluntary experiment and you have the right to withdraw for any reason and at any time.

Equipment Set-up
Today, we will ask that you take the seat position pre-arranged from your measurements last day. Are you still comfortable?

Next, let's verify that your eyes are horizontal with this point (refer to the center point of the tracking task as marked on the screen). You can adjust the height of your chair if you desire.

The foot pedal is in the same position as it was last day. Rest your right foot on the accelerator pedal, is it still comfortable?

Tracking-alone practice trials

Again today you will be asked to complete a number of trials that approximate the real task of driving. If you recall, your task will be to keep the red car still and centered in the middle of the black box marked on the lane. The car will be moving randomly up and down, and left and right in the lane. Your job is to compensate for these movements and keep the car still in the box.

To move the car: left: turn the steering wheel to the left.
right: turn the steering wheel to right.
forward in the lane: push the steering wheel forward
backward in the lane: pull the steering wheel toward you

Just as you did last day, you have to constantly watch out for pedestrians and other vehicles that may be on the roadway. Again, if you see anything on the roadway, press the brake pedal as fast as you can. The car icon will not actually stop, but your brake press will be recorded.

The acceleration of the car is programmed so you can rest your foot on the accelerator, but it will not affect the speed of the car. This is just a practice trial so you can regain the feel for the car and the steering wheel.

2 five minute tracking alone trials

Display Tasks

In addition to keeping your car in the center of the lane and responding to cars and pedestrians on the roadway, you are also required to retrieve information from the HUD. A different task will be presented than last day but again, the first will be shown about here on the screen (point to HUD location). This approximates the location of a real HUD. The second will be shown about here (point to HDD location), and will approximate the location of a real instrument panel in a car. You will never receive both at the same time, and I will tell you before each trial which one you should expect.

Verbal-Memory Display Task Alone

Each trial will start by displaying a set of red letters for 5 seconds. Your task is to memorize these red letters. After 5 seconds, the letters will disappear. Then, three green letters will be presented at the same time in the display and you will be required to determine if ANY ONE of the green letters was among the red letters you memorized previously. If any one of the green letters was among the red letters, press the right button on the steering wheel. It is marked with a "Y" for 'Yes, the letter was in the memory set'. If you do not think any of the green letters was among the memory set, press the left button, marked "N" for 'No the letters were not in the memory set'.

The letters will remain on the screen for 5 seconds, at which time it will automatically disappear whether you have responded or not. You can still respond, even after the display has disappeared. It is most important that you are accurate so be sure of your answer. Remember, I am also recording your reaction time as well, so respond as accurately and as quickly as you can.

Do you have any questions? If no, repeat: So remember, if ANY ONE of the green letters were among those you memorized, press the right button. If none were in the memory set, press the left button. These are just for practice. For now, you can ignore the car you do not need to steer for this trial.

On this trial, there will be two red letters presented in the memory set.

2 blocks of 12 easy verbal-memory trials - alone

This trial will be the same as before, except there will be 5 letters to memorize. It will be presented in the HUD/HDD also.

2 blocks of 12 difficult verbal-memory trials - alone

Dual task Practice Trials

It is now time for a combination of all the tasks you have learnt. You will be required to keep the car still and centered in the target box. A pedestrian may appear anywhere on the roadway and at any time. Brake as quickly as you can to the pedestrian on the roadway, and return to driving. Just like in the real world, your first priority always is to drive. This involves controlling your car and braking if you see pedestrians on the road. You should always ensure that these tasks are under control before answering the 'letter' task. Remember, I am recording accuracy and speed of the letter task.

Re-confirm that participant understands that driving (controlling the car and braking for the pedestrian) comes first and responding to the display task is secondary.

2 blocks of 12 easy verbal-memory task and tracking

2 blocks of 12 difficult verbal-memory task and tracking

Set One

Now, we are about to embark on the experimental trials. These trials will be the same as the ones you just completed.

Again, you are to remain at the task until the screen goes blank. When the screen goes blank, you may rest your eyes by changing the focus point. For example, you may want to look at the far wall for a few seconds. Please do not get up and leave the computer between blocks.

We will do this six times. At the conclusion of the sixth block, you will be permitted to take a five to ten minute rest break.

Are you ready? Remember, driving and braking for pedestrians always come first.

Verbal-Memory Trials in the HUD (orders 1-4 counterbalanced)

1 easy display task block
2 easy display task block
3 hard display task block
4 hard display task block

Verbal-Memory Display Irrelevant Trials

Now the letters will continue to appear in the HUD while you are driving. This time just ignore them. You do not need to press the response buttons. Please continue with the tracking task and brake for pedestrians as before.

5 display-irrelevant block
6 display-irrelevant block

OK, you may now take a rest period of approximately five minutes. You may get up and stretch.

5 to 10 minute rest break

Set Two

Please return to your seat at the apparatus and make sure that you are sitting in the same position. When you have returned to your comfortable position, I will re-measure your position to ensure you are sitting the same distance away from the computer.

We will begin the second set now. The trials will be exactly the same as before, except this time, they will be presented in the HDD (point to location on screen).

Verbal-Memory Task Alone

Just so you get used to the new location, these trials will let you practice the letter task, by itself. Remember, press the right button if ANY ONE of the letters was in the memory. Press the left button if none was.

1 block of 12 easy verbal-memory task alone trials

This trial will be the same as before, except there will be more letters in the memory set. It will be presented in the HUD/HDD also.

1 block of 12 difficult verbal-memory task alone trials

Dual task Practice Trials

Now we will try practice the letter task along with the tracking task. Remember that driving (controlling car and braking for pedestrian) comes first and responding to the letter task is secondary. Are you ready to try these tasks together? They are just for practice.

This time, the memory set will have two letters.

2 blocks of 12 easy verbal-memory trials and tracking

OK. Same thing again, this time, the display will include 12 lines. Still just for practice.

2 blocks of 12 difficult verbal-memory trials and tracking

We will begin the experimental trials for the second set now. Remember driving and braking are more important that the letter task.

Verbal-Memory Trials in the HDD (orders 1-4 counterbalanced)

1 easy display task block
2 easy display task block
3 hard display task block
4 hard display task block

Verbal-Memory Display-Irrelevant Trials

Now the letters will continue to flash on the screen while you are driving. This time just ignore them. You do not need to press the response buttons. Please continue with the tracking task and brake for pedestrians as before.

5 display-irrelevant block
6 display-irrelevant block

Summary

Thank-you very much. That is all for the experiment.
The purpose of the study was to examine the attentional effects of driving with an automobile HUD. There have been some reports that HUDs in aircraft have distracted the pilot and caused accidents.

Did you find driving and completing the HUD tasks easier, harder, or about the same as the HDD tasks? Clarify what participant meant.

In the trials which I told you to ignore the display task and just drive and brake for pedestrians, did you have any difficulties doing this? Was it harder for the HUD or the HDD, or was there any difference?

Do you have any questions? Thank-you very much for your help. I really appreciate the time you took to help me out.